

Solar Astronomy

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0. EXECUTIVE SUMMARY

The following is an abbreviated overview of our Panel recommendations, including the priority ranking of major missions, brief descriptions of these major projects, and a summary of recommendations regarding small-scale science, theory, and programmatics.

0.1 Strongly-supported Major Ongoing Projects

- Global Oscillations Network (GONG); cost: \$15M; start: 1987
- Solar Heliospheric Observatory (SoHO); cost: \$211M; start: 1988

• *GONG*. The Global Oscillations Network Group will produce definitive observations of solar global oscillations (p-modes), based on an Earth-encircling network of automated observing stations. The major aim is to reduce the effects of sidelobes (by dramatically increasing the time during which the Sun is observed), thus increasing the S/N, and making mode measurements much easier (and more reliable). These measurements, in conjunction with the on-going and planned solar neutrino experiments, allow us to peer into the solar interior, and thus allow us to test our understanding of how a star like the Sun is constructed.

• *SoHO*. The Solar Heliospheric Observatory contains coronal imagers and spectrometers, and a helioseismic instrument, and will be placed at the L1 Lagrangian point. It is a European spacecraft, but has U.S. participation in the form of instruments, ground support, and subsequent data analysis. This observatory has probably the best "shot" at observing g-modes (which will allow us to probe the deep interior), as well as the lowest-degree p-modes. In addition, the solar imaging instruments on SoHO are designed to look in great detail at a totally different aspect of solar activity than is normally examined, namely the mass outflows. They will also be able to look at the "closed" corona, and here their principal virtue is their spectroscopic capabilities, combined with imaging, which also allows detailed density and temperature diagnostics to be performed. SoHO will be able to measure temperature and density of coronal material out to several solar radii; to measure outflow velocities; and possibly to measure motions with sufficient accuracy that one could detect with waves in the atmosphere. Thus, these instruments will directly address the recalcitrant problem of accounting for the acceleration of the solar wind.

0.2 New Ground-based Solar Projects

1. High Resolution Optical Imaging (LEST); cost: \$15M; start: 1991
2. Large-aperture Solar IR Telescope; cost: \$10M; start: 1996

• *LEST*. Our highest priority ground-based project is a new moderate-to-large-aperture adaptive-optics telescope in the visible region. This entails:

- (a) a vigorous development program in adaptive optics, based on the existing facilities;
- (b) the development of a moderate to large-aperture high-resolution telescope, either separately or jointly with other countries. The United States is now a participant in the Large Earthbased Solar Telescope

(LEST) consortium, which plans to build such a telescope starting in 1991. Contingent upon progress in the adaptive optics area, we propose to contribute up to 1/3 of the total cost of that telescope. The main improvements over existing telescopes will be in resolution (down to $0.1''$), intrinsic polarization (less than 1%), and improved detectors. LEST will thus function as a high angular resolution ground-based optical imaging tool for examining flow-magnetic field interactions; for example, its polarimetric capabilities will enable it to measure Stokes parameters with higher accuracy than OSL, though over a much smaller field of view.

• **LARGE-APERTURE SOLAR INFRARED TELESCOPE.** The infrared solar spectrum offers several innovative ways to study solar magnetism. The opacity minimum at 1.6 microns gives us the deepest look into the solar photosphere. At 12 microns, emission lines arising from highly excited states of magnesium give us our first good look at magnetic regions that are difficult or impossible to probe in the visible. A further powerful advantage for magnetic field research in the infrared is the quadratic wavelength variation of Zeeman splitting. Our proposal again entails two distinct objectives:

(a) Acceleration of existing programs for the development of focal plane instrumentation suited to measure magnetic fields in the infrared;

(b) Building a larger telescope than the 1.5m McMath (because of the improvement of seeing that occurs in the infrared, combined with the decreasing resolution of a fixed aperture at increasing wavelength, and the decreasing photon flux per spectrum line doppler width in the infrared), which means one of the following three options: (i) join with our nighttime colleagues in construction of a 10m class telescope capable of doing solar infrared daytime work (with suitable protection); or (ii) construct a new, large-aperture solar infrared telescope, possibly in combination with a large-aperture reflecting coronagraph; or (iii) upgrade the McMath telescope to a 4m aperture.

This facility will allow us to probe the 3-D structure of magnetic flux tubes in the solar surface layers, and thereby permit us to understand the processes which lead to these highly fragmented structures in the solar photosphere.

0.3 New Space-based Solar Projects

0. Orbiting Solar Lab (OSL); cost: \$500M; start: 1992

1. High-energy Solar Physics mission (HESP); cost: \$200M; start: 1995

2. High-resolution Coronal Imager (Context); cost: \$250M; start: 1998

• **OSL.** The Orbiting Solar Laboratory represents a marriage of a high angular resolution optical telescope with a high angular resolution UV spectrometer and X-ray imager on a free-flying polar orbiter. The main objective of OSL is to image the solar surface layers with a sufficiently high angular resolution ($0.1\text{--}0.3''$) so as to observe directly the interactions between surface motions and the magnetic fields on the solar surface. To date, we have only been able to do this from the ground (through the highly obscuring terrestrial atmosphere) and on one brief Shuttle flight; OSL will allow us to view the interactions we believe give rise to virtually all of solar activity over time scales comparable to the duration of the solar activity cycle. The physical processes we want to understand, and which will be observed with this mission, are: (a) The formation of magnetic flux bundles — we want to understand why solar magnetic fields are so highly spatially intermittent; (b) the evolution of surface magnetic fields — we want to understand how the distortions of surface magnetic fields by the surface convection can lead to plasma heating, including the creation of a multi-million degree corona enveloping the Sun; and how the process of magnetic field evolution proceeds (we know that solar magnetic fields must decay, but the observed decay rate is many orders of magnitude larger than what classical theory would predict.)

• **HESP.** The High Energy Solar Physics mission will carry out high-resolution spectroscopy and imaging of solar hard X-rays and gamma-rays, and will detect neutrons. It will image X- and gamma-ray sources with resolution better than $1''$, and will resolve spectral features with $E/\Delta E \sim 1,000$ up to energies of 10 MeV. HESP will study the processes of nonthermal energy release in the active solar atmosphere by observing the X-rays and gamma-rays produced by particles accelerated concomitantly with flare energy release. We know that in solar flares the release of nonthermal energy is mediated by efficient particle acceleration, that energy is transported rapidly by the accelerated particles, and that the acceleration and transport must result from complex interactions of plasma with shocks, turbulence, and rapidly varying electric fields. However, we do not understand the detailed nature of these processes, nor can we reliably differentiate among different mechanisms. We must determine the location of the site or sites of particle acceleration observationally,

we must define the properties of the particles directly from the observations, and we must have a clear picture of the relevant magnetic configurations. Observations with high spatial resolution will allow the localization of the sources of the particles and the tracing of their transport paths. Observations with high spectral resolution will allow the deciphering of the rich information encoded in gamma-ray lines, such as energy spectra, angular distributions, abundances, and energy content of the accelerated particles. Because of the proximity of the Sun, the study of the solar high-energy processes provides one of the best techniques for investigating similar processes which are known to play a dominant role at many astrophysical sites. HESP has a definite time-critical need — it must be flown by the year 1999 to take advantage of the next solar maximum. For this reason, we aim at a modest mission (in the "intermediate class", in the context of NASA/Space Physics Division plans). HESP will consist of a single major high-energy instrument capable of carrying out high-resolution imaging and spectroscopy simultaneously. It is by virtue of this simplicity of design that a mission in orbit by 1999 is possible.

- *High-resolution Coronal Imager (Context)*. The *Context* mission addresses a major problem in astrophysics: How are hot plasmas in stellar atmospheric structures created? *Context* takes advantage of the opportunity created by the measurements of *Solar Probe*, which will fly to within 4 solar radii of the photosphere and conduct *in situ* measurements there. Through high-resolution imaging and spectroscopy, *Context* can identify the structures through which *Probe* has flown, in order to understand the environment of *Probe*'s particles-and-fields measurements. Such a combination of *in situ* and remote sensing will be unprecedented in astrophysics.

0.4 Strongly-supported Major Interdisciplinary Projects

- Solar Neutrino Experiments; no costs available
- mm Array; cost: \$115M; start: 1991
- *Neutrino experiments* refer here to the panoply of solar neutrino experiments supported by DOE and NSF, many carried out in collaboration with foreign scientists, including the Homestake mine experiment, the Japan/US collaboration Kamiokande II, the Canadian/US collaboration in the Sudbury experiment, the Gallium experiments, and so forth. The long-standing solar neutrino problem involves a remarkably broad range of physical issues, from stellar structure and opacity calculations to the physics of neutrinos themselves. More recent data have only deepened the mystery of these particles, as the possibility of correlations of the solar neutrino flux with the solar activity cycle has been raised. The discrepancy between what we observe and what can be explained by theory, is so substantial, and is so basic to physics, that the new experiments must be assured of continued funding.
- The *mm array* is a facility which solar radio astronomers are enthusiastically looking forward to sharing with their astrophysics colleagues. Its main capability will be to allow imaging of the solar outer atmosphere at radio wavelengths with a resolution comparable to the what can be done at other wavelengths (from the optical to X-rays), and to do so in a wavelength window which has been essentially unexplored. A particular feature of observations at these wavelengths is that one can look "deeper" into the atmosphere than at longer wavelengths.

0.5. OTHER RECOMMENDATIONS AND POLICY CONCERNS

The Solar Panel also focussed on a number of issues not tied to the larger projects just discussed:

0.5.1 *The role of small-scale projects*. The Solar Panel strongly encourages the continued vigorous support of small-scale scientific projects, such as balloon and sub-orbital rocket projects; small PI-class space missions; and strong individual investigator grants programs at both NSF and NASA.

0.5.2 *University revitalization*. Solar physics is poorly represented at universities, a demographic fact which bodes ill for the future of the discipline. We therefore strongly support efforts to fund graduate students, such as the NASA Graduate Student Research Fellowship program; encourage more flexibility on the funding time period for NSF fellowships; and advocate stronger research ties between the universities and the national research centers.

0.5.3 *Funding flexibility*. We urge NASA and NSF to allow greater flexibility in the duration of funding periods.

0.5.4 *Balanced support of experiments and theory.* Balanced development of solar physics calls for consistent and realistic support of both theory and experimental efforts, including the support of theoretical work which is not directly tied to observational programs.

0.5.5 *Interdisciplinary research.* Neither the NSF nor NASA have a regular mechanism in place for handling interdisciplinary research programs. This is a particularly deeply felt problem in solar physics because solar physics research by its very nature tends to cross the discipline boundaries defined by the agencies. We therefore urge that provisions be made to allow such research programs access to funding.

0.5.6 *Access to large-scale computing.* Despite the vastly improved access to supercomputing afforded by the NSF Supercomputer Centers, it remains difficult to obtain large (> 200 hrs) contiguous allocations of supercomputer time. We therefore urge that exploratory programs initiated by NASA/Ames, NASA/Goddard, NCAR, and others to address this problem be strongly encouraged.

0.6. ENABLING TECHNOLOGIES

The following examples are just illustrative of the range of technologies with which solar physics is involved, and in which it plays a leading role. We strongly endorse a continued vigorous program in technological developments.

- Active control of large structures in space. This will be needed in order to carry out the Pinhole Occulter Facility (P/OF), a major imaging facility at hard X-ray and gamma-ray energies with sub-arcsecond capabilities.
- Adaptive optics, optimized for relatively low-contrast, extended images.
- Capabilities for analysis of extremely large data sets (> 1 Terabyte).
- Improved, new-generation detectors for high energies (e.g., wide-band gap semiconductors, gamma-ray channeling detectors, etc.); and at infrared wavelengths (large format CCDs).
- Further development of normal incidence EUV and X-ray optics for high angular resolution studies at these wavelengths.

1. AN OVERVIEW OF MODERN SOLAR PHYSICS

1.1 General Perspectives

Recent theory and observation have established that the Sun is a complex dynamical structure, whose interior represents an active and mysterious universe of its own. There is no reason to doubt the basic features of stellar structure models, but it must be remembered that the ideal standard stellar model contains many arbitrary assumptions. The Sun is the only star that has been studied in detail, and the only detailed information we have is from scrutinizing its more or less inscrutable exterior. Its interior possesses internal degrees of freedom that are only gradually being discovered and described, and, once described, are only gradually being understood. Present knowledge of the interior of the Sun and stars is based largely on simplified static models constructed from the theoretical properties of particles and radiation as we presently understand them. Parameters can be adjusted to provide a static solar model whose radius and surface temperature agree with observation, and which represents a starting position for the next phase of the inquiry into stellar physics. This next phase concerns the dynamic and magnetic aspects of a star, a phase which is already well underway, and which is the primary focus of our report.

Now the dynamical effects ignored in the static models are already suggested by these models. Thus, for instance, the calculated temperature gradients indicate the existence of the convection zone, extending from the surface down a distance of about 0.3 solar radii. The gas continually overturns and operates as a heat engine whose work output is not subject to the usual thermodynamic limitations that apply to thermal energy. The activity at the surface of the Sun is a direct manifestation of this convective heat engine, which produces such diverse phenomena as sunspots, flares, coronal transients, the X-ray corona, and the solar wind, largely through the magnetic field as an intermediary. It seems not to be generally recognized in the astronomical community and elsewhere that the precise causes of solar activity are not yet reduced to hard science. For instance, it cannot be stated why the Sun, or any other solitary star, is compelled to emit X-rays, nor is it understood why a star like the Sun is subject to a mass loss of 10^{12} gm/sec. Indeed, it is not altogether clear why the Sun chooses to operate a 22-year magnetic cycle, producing the other aspects

of the activity largely as a by-product. This means, then, that we do not understand the origins of stellar X-ray emissions; this branch of X-ray astronomy, with its remarkable powers of penetration into the active component of the universe, is for the present limited largely to phenomenological interpretation. Indeed, the present ignorance of the Sun reflects the general lack of progress in understanding stellar activity of all kinds. We cannot fully interpret nuances of the surface emissions of the distant stars until we understand the physics of surface activity through close scrutiny of the Sun.

However, the problems are deeper than the puzzles of surface activity. There are the mysteries posed by the different surface abundances of Li, Be, and B and in more stable elements such as Ca and Fe in some F and G dwarfs. There is the mystery posed by the theoretical evolutionary brightening implying that the Sun was 30 percent fainter 3 or 4 $\times 10^9$ years ago, while over the same period of time, mean temperatures on the terrestrial equator have not varied more than a few degrees.

Turning to more direct problems, observations of the solar neutrino emission have failed to corroborate the conventional theoretical models of the Sun. The failure to do so has stimulated a careful review of the theoretical complexities and uncertainties of the model, leading to significant downward revisions of the predicted neutrino flux. Nonetheless the present discrepancy between the observed and predicted neutrino emission seems to be stuck at a factor of three. Until that dilemma is resolved, we cannot be sure of the rest mass of the neutrino or of the amount of the dark matter in the universe. We cannot be sure of the theoretical evolution of a star on the main sequence. We cannot be sure of the age of globular clusters or of the age of the galaxy. We cannot be sure of any theoretical interpretation of anomalous abundances in main sequence stars.

Helioseismology shows promise of providing a detailed and quantitative probe of the physical conditions (temperature, density, mean molecular weight, angular velocity and magnetic field) throughout the entire Sun. Complete success depends upon suitably long unbroken runs of data and on the detection and identification of g-modes. The analysis of the data currently available points to peculiar and puzzling effects, including interior velocity fields inconsistent with detailed hydrodynamic simulations and with classical dynamo theory. The frequencies of the p-modes differ by many sigmas from those calculated from the standard models of the solar interior. How drastic will be the necessary revisions to the standard solar model is a matter of conjecture. The present rapid development of seismological probing of other stars is an exciting and important adjunct to the exploration of the interior of the Sun.

It should be emphasized that there is far more at stake than the standard model of the solar interior. Our knowledge of the static structure of most stars is founded on the success of the solar model, and it is on the theoretical static structure of stars that our ideas of the age and evolution of the galaxy are based. From the broadest perspective, one of the fundamental tasks of solar physics is to develop independent observational checks on this central bastion of astrophysical knowledge.

Now, the remarkably active state of the solar periphery, driven by the convective heat engine, has been studied with increasing angular resolution, spectral resolution and wavelength range for several decades. Knowledge has expanded enormously, without, however, bringing immediate theoretical understanding. Solar activity, like the Earth's weather, is a tempestuous and complicated affair. To obtain some measure of the possible theoretical complexity, note that the Reynolds number N_R of the convective heat engine is of the order of $10^{12} - 10^{13}$, which means that the fluid is active on all scales from one solar radius R down to the fraction $10^2/N_R$ of R , or ≈ 10 cm. Hence, the convection has approximately $(N_R/10^2)^3 = 10^{30} - 10^{33}$ degrees of freedom, and for complete numerical simulation would require a grid with $N_R/10 = 10^{11} - 10^{12}$ intervals in each of three dimensions. What is more, the magnetohydrodynamic Reynolds number N_M is 10^{10} , whereas the terrestrial laboratory can achieve no more than 10^2 or 10^3 , so there is no general body of knowledge from which the subtleties of solar magnetic activity can be interpreted. The enormous heat flux in the convective zone producing the superadiabatic temperature gradient and driving the convective heat engine on all scales, and the extreme magnetohydrodynamic effects of solar activity combine to provide a dynamical scenario of exotic character that can be understood only after it is described and studied in detail - it is far too complex for *a priori* predictions. First, detailed observations are required to describe the situation. Then, numerical modeling and theoretical studies of individual dynamical effects can be brought to bear. That is the nature of the activity of a star: There is no single effect, no single new principle that throws open the gates to a flood of understanding. The behavior of a convective, highly conducting fluid is a whole field of physics in its own right, which requires concerted close theoretical and observational study in its own right, progressing past dozens of "milestones" and enjoying dozens of "breakthroughs." The milestones

and breakthroughs already add up to an impressive body of knowledge, but represent only a beginning.

A particularly important revelation occurred about two decades ago, with the realization from detailed observational and theoretical considerations that, outside sunspots, the magnetic field at the surface of the Sun, rather than being the expected continuum distribution, is effectively discontinuous, composed of small individual intense and widely separated magnetic flux tubes of $1 - 2 \times 10^3$ Gauss. The measured mean field in any region then depends mainly on the distance between the individual magnetic fibrils, because the individual fibrils or flux tubes are too small (about 200 km diameter), for the most part, to be resolved in the telescope. The crucial information for understanding the large-scale behavior of the magnetic fields on the Sun (which are, it must be remembered, the perpetrators of the Sun's magnetic activity) are: (a) the origin and structure of the individual fibrils and (b) their individual motions. So the pursuit of solar activity becomes solar "microscopy". This is a field in its infancy, although with great potential through the development of adaptive optics on ground-based telescopes and the development of diffraction limited telescope systems in space. Indeed, the high resolution UV observations from space, although nowhere near the ultimate necessary resolution of 50-100 km, have already established the general occurrence of myriads of tiny explosive events (nanoflares) and high speed jets in the solar corona, providing a clue about the heat input that causes the corona. The individual bursts of energy ($10^{24} - 10^{27}$ ergs per event), and indeed the entire supply of energy to the corona, is evidently a result of the motions of the individual magnetic fibrils in the photospheric convection. The motions undoubtedly involve both jitter and intermixing of the individual fibrils, producing Alfvén waves and a general wrapping, respectively, of the lines of force in the fields in the corona. But at the present time, there is no direct measure of any aspect of the fibril motions, nor any direct detection of waves or wrapping in the coronal magnetic fields. Only the effects of the myriad of small explosive nanoflares can be seen. So the causes of the solar and stellar corona, although extensively developed theoretically, are still without a hard observational foundation.

Another important milestone was the *Skylab* discovery of frequent coronal transients, involving the eruption of matter from the low corona outward into space, often accompanied by flare activity at the surface of the Sun. Now many years later, we are beginning to realize that these mass ejection events apparently result from large-scale magnetic field eruptions – but why they occur is not clear. Further, the observations show clearly that coronal mass ejections and chromospheric eruptions (i.e., flares) can proceed quite independently. Thus, the coronal mass ejections reflect a form of solar activity not heretofore recognized. Their relation to the large scale evolution of the solar magnetic field – and to stellar magnetic changes – is not yet clear.

The remarkable X-ray photographs of the Sun, showing clearly the magnetic loop structure of the active corona and the interweaving coronal holes, have gone a long way toward formulating the problem posed by the existence of the active X-ray emission. Also, the high speed streams of solar wind issuing from the coronal holes demonstrate that the corona is active even outside of active regions. The X-ray and EUV studies of the solar corona, together with the discovery by the orbiting *Einstein* Observatory that essentially all stars emit X-rays, provide a profound scientific challenge as to why ordinary stars are compelled to such extreme suprathermal exploits.

The ability to release energy impulsively and accelerate particles is a common characteristic of cosmic plasmas at many sites throughout the universe, ranging from magnetospheres to active galaxies. Observations of gamma-rays and hard X-rays, radiations that can be unmistakably associated with accelerated particle interactions, as well as the direct detection of accelerated particles, such as cosmic rays, strongly suggest that at many sites a significant – and in some cases even a major – fraction of the available energy is converted into high-energy particles. Detailed understanding of the processes which accomplish this is one of the major goals of astrophysics.

Solar flares offer an excellent opportunity for achieving this goal. A large solar flare releases as much as 10^{32} ergs, and a significant fraction of this energy appears in the form of accelerated particles. It is believed that the flare energy comes from the dissipation of the non-potential components of strong magnetic fields in the solar atmosphere, possibly through magnetic reconnection. Immediate evidence for the presence of accelerated particles (electrons and ions) is provided by the gamma-ray and hard X-ray continuum emissions which result from electron bremsstrahlung, and by gamma-ray line and pion-decay emissions from nuclear interactions. Nuclear interactions also produce neutrons, which are likewise directly observable at Earth. The accelerated charged particles enter interplanetary space and arrive at Earth somewhat later, delayed by their circuitous paths of escape from the magnetic fields of the flare. The wide variation of the relative

abundances of some isotopes and atomic species among the accelerated particles provides an indirect but detailed view of the physics operating within one of the flare particle-acceleration processes. These high energy emissions are the best tools for studying acceleration processes in astrophysics. Solar flares are one of the very few astrophysical sites where it has been possible to study simultaneously the acceleration of electrons and protons, and only for solar flares can the escaping accelerated particles be directly detected and correlated with the electromagnetic radiations produced by the interaction particles. In addition, lower-energy emissions (soft X-ray, EUV, UV, and radio emissions), which are also observed from flares, reveal much of the detailed properties of the ambient plasma (e.g., temperature, density, and magnetic configuration) before, during, and after the flare.

This is the broad view of the mystery of the Sun and the stars. The specifics are complex, but it is essential, if we are to grasp the scope of the problem posed by the Sun, to spell out these complexities in somewhat more detail. The next section, then, details some of the specific problems, measurements, observations, and theoretical studies that are necessary along the way to probe the mystery.

1.2 The Frontiers and Goals for the 1990s

By the year 2000 we hope to have a fairly detailed picture of the structure and dynamics of the solar interior, a better understanding of how the Sun generates magnetic fields, considerable measurements of how magnetic fields modulate the smooth outward flow of energy, a better description of the morphology of flaring plasmas, and some predictive capability for the flow of non-radiative energy through the heliosphere to Earth. These and other advances will be achieved by observational improvements in spatial resolution, temporal coverage, and new exploitation of radio, infrared, EUV, and X-ray spectral regions. Up to the present moment, the Sun has become increasingly mysterious the more we have studied it; by 2000 AD, we may reasonably hope to begin closing in on some of the more important mysteries.

As in any subfield of astronomy, there are more solar problems ripe for attack, and hence more projects in this report, than can be accomplished in a decade. Uncompleted tasks will form the basis of a program for 2000 and beyond. There is no likelihood that access to space will become rapid, cheap, frequent, or reliable enough to replace the need for a strong ground-based program. Hence, both space-based and ground-based components will be required in solar physics for several decades into the future.

In this section we focus on the principal specific goals for solar research which we believe are most important and also realizable in the decade of the '90s or shortly thereafter. This list will then determine the specific initiatives we will recommend in Sections 2 through 5. For convenience, we deal with the three principal components of the Sun – interior, surface layers, and outer layers – in sequence.

1.2.1 The Solar Interior

Two powerful and complementary techniques are available for probing the solar interior: neutrino spectroscopy and helioseismology. The flux of high energy neutrinos has been measured since the late 1960's. A discrepancy of about a factor of three between observations and model predictions gives rise to the well-known solar neutrino problem. Significant progress toward solving this problem can be made by a new generation of detectors that will allow the spectrum of solar neutrinos to be measured. An appropriate goal is to measure, by the end of the decade, the flux of solar neutrinos and its possible time variation as a function of energy, from the low energies associated with the neutrinos resulting from the main p-p reactions up through the energies of the ^8B neutrinos long-studied by the chlorine experiment. In addition, the fluxes (and their possible time variations) should be understood in terms of the structure of the interior (and its possible time variations), as well as the particle physics of the neutrino.

Helioseismology uses the frequencies of millions of normal modes of oscillation of the Sun as probes of the structure and dynamics of the interior. Since 1975, exploration of much of the solar interior has been done using this technique. Better measurements are required to explore both the deep and shallow interior regions as well as to refine the present fairly crude picture of the middle regions. A major goal is to discover why the theory of stellar structure and evolution fails to correctly yield either the structure or the dynamic picture now emerging from helioseismology. Some of the required measurements can be done only from space but others can be done from the ground more effectively. A newly emerging technique is seismic imaging of local regions on the Sun. This promises to give us the first subsurface views of solar activity, which should revolutionize our understanding of enigmatic features such as sunspots. A realistic goal is, by the end of the decade, to have made accurate measurements of the entire spectrum of p-modes; to have developed a

new solar model consistent with these data within their errors; to have determined empirically the internal rotation as a function of depth and latitude; to have obtained a quantitative theoretical understanding of the physical processes giving rise to this differential rotation; to have detected the elusive large-scale circulation flows in the deep convection zone; to have mapped the three-dimensional structure of surface active regions and sunspots; and (if they penetrate to the surface with observable amplitude) to have made the initial detection of g-modes generated in the deep interior. This ambitious set of goals is made realistic because of the extraordinary observational and theoretical progress in helioseismology made in the '80s, coupled with realistic expectations for observational and theoretical capabilities to be developed in the '90s.

The cycle of solar magnetic activity is believed to arise in the interior by a combination of differential rotation and cyclonic convection acting on magnetic fields. More accurate and higher resolution measurements of surface magnetic fields are required to understand how magnetic flux evolves and is dissipated from the surface as part of the solar cycle. Also needed are accurate measurements of mass flows both on small and large scales to gain a better understanding of the role of magnetoconvection. Such observations, combined with some of the helioseismic results described above, should go a long way toward reaching the goal of an accurate model of the solar dynamo. A realistic goal for the '90s is one which has been sought for decades: finally to obtain a real physical understanding of the origin and nature of magnetic activity in the Sun and stars.

1.2.2 The Solar Surface

Observations have shown that the solar surface layers – from the chromosphere to the corona – are permeated, heated and controlled by the magnetic field rooted in the photosphere. The physics of this region is complicated by large density and magnetic variations and violent mass motions. A major observational problem is the difficulty in making accurate physical measurements in the face of spatially blurred observations. Physical quantities deduced from such blurred measurements may apply to an average within the measured volume of the quantity, but because of extreme nonlinearities they may apply to no physically realizable state at all. It is little wonder that important problems such as heating of the upper solar atmosphere or storage of magnetic energy and its violent release in flares have not been solved. The frontier in this research is very much controlled by how small a volume can be measured accurately. While space offers the most certain route to improvement, the development of adaptive optics promises significant benefits using ground-based telescopes. A realistic goal for the '90s is to obtain a clear physical understanding of the interaction of magnetic fields and convective motions at and immediately beneath the surface, and specifically to understand the surprising shredding of the field into spatially intermittent “flux knots,” which appears fundamental both to the evolution of surface magnetic fields and to their consequences for atmospheric heating.

New measurement techniques will also be needed to characterize accurately the physics of the lower atmosphere. Particularly important will be observations of the magnetic field as a vector varying with height and time, along with corresponding vector mass motion measurements. The technology to make such measurements is under active development at several observatories. Advantages of diverse spectral regions, from the extreme ultraviolet through the infrared to mm wavelengths, are being exploited. Extremely important is the capability to relate physical conditions measured in the surface layers (through visible and infrared data) to conditions in the overlying heated chromosphere (through UV, extreme UV, and mm data); the data must have adequate spatial and temporal resolution to isolate physically near-homogeneous regions and to establish cause-and-effect relations between phenomena at the various levels. A reasonable goal for the end of the decade is to make substantial progress in developing and testing a specific physical description of the magnetohydrodynamic processes giving rise to atmospheric heating in these layers.

1.2.3 The Outer Solar Atmosphere: Corona and Heliosphere

Our understanding of the corona and heliosphere was revolutionized by space observations during the last three decades. While much was learned, we still do not have a good understanding of what compels the Sun to produce a hot, X-ray emitting corona. Evidently most other stars also have coronas. Observations have demonstrated that magnetic fields play a controlling role in the morphology and large-scale dynamics of the solar corona. There is also evidence, but not proof, that magnetic processes are responsible for supplying the energy to heat the corona and to produce violent events such as flares and coronal mass ejections. The key to further progress lies in obtaining improved observations on all accessible spatial and temporal scales, but particularly on the smallest size scales. Progress in X-ray and gamma-ray imaging promises to allow

major advances in our observational understanding of the corona's structure, and of the relation between heated plasma and the sites of energy release.

The outer corona merges into a heliosphere that dominates interplanetary space. The heliosphere is Earth's non-radiative connection to the Sun, and events within it are of considerable practical as well as scientific interest. Much has been learned about the structure, dynamics and physics of the heliosphere by combining in situ and indirect measurements with correlative studies of driving phenomena at the solar surface and in the lower atmosphere and corona. The same cannot be said for violent events such as coronal mass ejections that occur frequently during active times of the solar cycle — better observations from the photosphere through the heliosphere, involving in particular coordinated in situ and remote sensing observations, are required for significant further progress.

Appropriate goals for the decade of the 1990s include localizing coronal energy release sites, understanding in detail the mechanism of solar wind acceleration and fixing the height above the surface at which it occurs, and determining how the speed of the resultant wind depends on magnetic geometry. Finally, an extremely important goal is to take advantage of the activity maximum around 1998-2002, using state-of-the-art imaging instruments at X-ray and gamma-ray energies, in order to achieve a major advance in our understanding of the basic mechanisms of solar flares, including very high energy particle acceleration.

1.2.4 The Solar-Stellar Connection

It should be emphasized in this overview of solar physics that the solar-stellar connection is an important part of the physics of the Sun and the physics of stars in general. For we may safely assume that most, if not all, rotating and convecting stars would prove as active and mysterious as the Sun if we could observe them as closely. These stars do not fail to exhibit great complexity in those aspects that can be studied. As already noted, it is astonishing to see that some stars support gigantic flares and starspots. Some exhibit mass loss enormously greater than the Sun. Essentially all of them exhibit X-ray coronae, from which we may infer that their coronal gas expands along the more extended lines of force, carrying the field into space to form a stellar wind much like the solar wind. The general existence of X-ray coronae implies the same nanoflares and microflares and the same coronal transients as can now be observed on the Sun, although there is no foreseeable means for observing them individually on the distant stars. The same complex magnetohydrodynamic and plasma processes must occur. The same puzzles concerning their internal structure, their internal rotation and their dynamo confront us, except that it is not possible to come so directly to grips with these puzzles as it is for the Sun. The best that can be foreseen is to understand the Sun and then perhaps to infer the solutions for the other stars. It is essential, therefore, to study the oscillations and seismology of the other stars, to monitor their activity cycles over long terms, and to make precise measurements of their rotation rates. Only in this way can we discover their individual quirks as well as determine the "average" behavior of each class of star. The deviation of the individual from the average provides insight into the variable conditions under which stars are formed, which then helps to understand the idiosyncrasies of the Sun. Other stars of different ages may provide an idea of the Sun in its youth, to be compared with the geological record for clues to the effects on the planetary environment. The spindown of the Sun at an early age may have involved profoundly different conditions from those that obtain today. In a similar vein, it appears that the Sun occasionally passes through centuries of suppressed activity (e.g., the Maunder Minimum), and centuries of enhanced activity. The human research program cannot encompass such fundamental long-term shifts in the nature of the activity, so one must turn to the hundreds of solar-type stars to provide a record of the many different moods of the Sun in the span of a human lifetime.

Thus, as a direct by-product of obtaining the goals described above, we may anticipate corresponding great advances in our understanding of many long-standing problems of stellar physics. But beyond this "spin-off" result, it is reasonable to adopt the goal of making far more detailed studies of stellar phenomena related to those studied on the Sun, through emerging capabilities of stellar seismology, through stellar observations with new advanced ground-based and space instruments expected to be operational during the decade, and through continued monitoring of time-varying stellar magnetic activity of existing observatories.

In concluding this general appraisal of current problems in the physics of a star like the Sun, it is appropriate to make some general comments on the future beyond the listing of specific research goals as we perceive them today. Even though solar physics is sometimes thought of as a mature field, in the coming decade it may be as unpredictable and full of surprises as any astronomical discipline. The observational

techniques available in this closing decade of the 20th century have opened up entirely new horizons to solar research. It is too soon to guess where the neutrino observations will lead, but whatever the results of the present gallium detectors, the astronomical implications will be profound. Helioseismology may be expected to play an essential role in removing the ambiguities of anomalous neutrino fluxes, unless, of course, the discrepancy is entirely a matter of neutrino oscillations between three or more states, which would have deep cosmological implications. What is more, we can be sure that the investigation of the solar surface and the solar interior on so broad a front will provide surprises, perhaps of a fundamental nature. The present writing is based only on contemporary knowledge, and cannot anticipate what lies ahead when we probe into the unknown realm of the solar interior and the small-scale phenomena at its surface.

2. GROUND-BASED SOLAR PHYSICS

2.1 Introduction

For nearly 400 years the physics of the Sun has been studied from the ground. While much has been learned about the Sun – and by most astronomical standards it is well understood – the fact is that the Sun confronts astronomers with many unsolved puzzles, both old and new – a point made in some detail in the preceding discussion. Observations from the ground continue to play a major role in confronting these puzzles, many of which have consequences far beyond solar physics.

Within the general framework just discussed, we see the 1990s as the era in which ongoing key initiatives – discussed in Section 2.2 below – will be augmented by a major new initiative, which is needed to make really significant progress in our understanding of solar activity. This new “solar magnetohydrodynamics” initiative depends upon a concerted development program in high angular resolution optical observations and precision polarimetry, using existing ground-based telescopes; and aims for the establishment within this decade of a large-aperture ground-based optical facility – the Large Earth-based Solar Telescope – using adaptive optics techniques to image the solar surface in the subarcsecond range.

2.2 Status of Major Projects and Facilities

One major ground-based solar project is in progress: the Global Oscillation Network Group (GONG) project. It is aimed at a ten-fold improvement in the accuracy of intermediate spatial-scale helioseismology measurements for studies of most of the solar interior. The project is a community effort led by the National Solar Observatory. A prototype instrument will be completed early in 1991 and the next phase of the project is to build and install six identical instruments at selected sites around the world. Given timely funding, this network should be operational in late 1993. Observations and data reduction will continue for at least three years, to be followed by an intensive analysis effort by the helioseismology community. GONG and the helioseismology instruments to be flown on the SoHO mission in 1995 were designed to be complementary and interdependent: While GONG emphasizes intermediate spatial scale observations with a high duty cycle, the SoHO instruments emphasize large and small spatial scales difficult to observe from the ground. Thus, both projects are essential for the advance of helioseismology, and together can attain the helioseismology goals discussed in Section 1.2.1.

The U.S. program of solar physics includes a wide range of ground-based observational facilities operated by national observatories, federal agencies and individual universities. The national observatories with solar observing capabilities (the National Solar Observatory and the National Radio Astronomy Observatory) provide facilities that are publicly available to qualified scientists by peer review. These facilities generally have a scale that is not appropriate for a single university. Federal agencies (NASA, Air Force, Department of Commerce) operate solar facilities in support of various mission goals. These facilities are not generally available to the wider research community. The federally-funded High Altitude Observatory operates solar facilities for its own research programs, but also provides for the use of facilities to the community. Several universities operate solar observing facilities in support of the research of their faculties and students. The scope of these ranges from major, multi-purpose equipment to modest, single purpose instruments. The observational solar programs with two or more faculty members include the California Institute of Technology, California State University at Northridge, Michigan State University, Stanford University, the University of Hawaii, and the University of Maryland. Smaller programs (one faculty member) are found at Penn State University, University of Arizona, University of California at Los Angeles, the University of Chicago, and the University of Southern California.

The U.S. ground-based observational solar program led the world for most of the 20th century. This leadership role is now being challenged by the decline in funding in the US, and by other countries that are developing strong observational programs, most notably various European countries and Japan. The existing U. S. telescopes were built for the most part before 1970 and are equipped with focal plane instrumentation that has been upgraded but frequently dates to the 1970s or earlier. Nonetheless, these telescopes are important resources; with more modern focal plane instrumentation, many of the ground-based frontier projects for solar physics in the 1990s could be carried out with existing telescope facilities.

2.3 A Prioritized Ground-Based Program for the 1990s

2.3.1 Prerequisites

To keep the United States at the forefront of international solar research, the ground-based U.S. solar program for the 1990s must:

- focus clearly on the most important scientific problems which can be attacked with available technology, and the technology now under development;
- be able to translate the specific plans developed by the community into ongoing projects with some assurance of funding continuity;
- provide for a balance between the large-scale, community-based programs and smaller-scale research programs led by individual investigators;
- assure a balance between innovative new projects and the fulfillment of commitments to ongoing projects, including those which by their very nature are carried out over long spans of time, based on scientific merit;
- assure the training of solar scientists at a level commensurate with the anticipated program beyond the year 2000;
- encourage a symbiotic relationship between ground-based and space-based observers, and theoreticians;
- provide for the infrastructure needed to support the anticipated program, including an effective capability for reducing and analyzing the extremely large data sets which new generations of solar instruments (and numerical simulations) will provide.

2.3.2 Prioritization

With specific regard to our priorities for the U.S. solar research program in the 1990s, several factors must be kept in mind in addition to the primary constraint, namely that of merit:

- the priorities of ground and space-based research are interdependent;
- the priorities of the U.S. program depend on international programs and programs of other nations;
- the program is motivated by a mixture of long term and short term needs;
- the program balances major, moderate, small, and interdisciplinary initiatives;
- "major solar initiatives", as defined by the AASC, require multi-year commitments at the NSF division level, not just at the program level;
- "moderate solar initiatives", as defined by the AASC, require commitments at the NSF program level, typically for 2-3 years;
- "interdisciplinary initiatives", often very large projects, may be of interest to organizational units of NSF other than the usual solar funding sources;
- operational systems, such as the U.S. Air Force Solar Observing Optical Network (*SOON*), must be recognized as programs whose principal responsibilities are to monitor and report solar activity, rather than to support solar physics research. Nevertheless, in the past, solar research has benefited significantly from USAF willingness to provide, for example, *SOON* H α images for research purposes (e.g., Solar Maximum Year).

2.3.3 The Major New Initiative: Solar Magnetohydrodynamics, and the LEST.

A major scientific goal for ground-based solar research in the 1990s is to understand the physics of solar magnetic fields in the regions of the Sun that are observable from the ground. This is an ambitious and critical goal, and we propose that the major step be taken to reach it by building, together with international partners, a Large Earth-based Solar Telescope – the LEST.

Research in solar magnetohydrodynamics has the potential to revolutionize our understanding of solar and stellar activity, the outer solar atmosphere, and how the Sun affects Earth. The Sun is the only star

for which we can investigate the small-scale phenomena that dramatically affect the transport of energy and momentum through stellar atmospheres. One of the most important discoveries of solar physics in the last two decades has been the recognition that the solar magnetic flux outside sunspots is highly structured in the form of intense, isolated magnetic flux tubes. This structuring of the field evidently plays a key role in the heating of the outer solar atmosphere, the occurrence of flares, and the driving of the solar wind. Therefore, the small-scale structure of the magnetized atmosphere of a star is in large measure responsible for many of the large-scale phenomena that have long been observed but not understood. The Sun is the only star for which one can achieve the spatial and spectral resolution and photon flux necessary to measure all components of the magnetic field vector, from which the structure and density of magnetic fields can be observed, and their role in solar activity understood. In this sense, the Sun acts as a Rosetta stone for interpreting the ubiquitous stellar activity observed by *IUE*, *Einstein*, *EXOSAT*, and now *ROSAT* throughout the H-R diagram.

The Solar Panel has identified as its highest priority for ground-based solar research a major initiative in magnetohydrodynamic (MHD) studies of the solar photosphere and overlying atmosphere. The time is right for this MHD initiative in this decade because recent advances in telescopes, polarimeters, detectors, data processing, and radiative transfer theory offer ways to break through barriers that up to now have seriously impeded progress. The major impediments have been inadequate spatial resolution for extended time periods, incompletely compensated telescope polarization, difficulty in obtaining measurements of the full vector magnetic field over a range of heights, and oversimplified interpretation of measurements. High resolution should be achievable through the use of adaptive optics systems with existing telescopes and with new, large-aperture solar telescopes located at excellent seeing sites. Telescope polarization can now be compensated to the 0.1% level at existing telescopes and to the 0.01% or better level in new, low polarization designs. Highly efficient modulators and detectors offer orders-of-magnitude improvements over most existing equipment for the measurement of the full vector magnetic field. Additional layers of the solar atmosphere have been made accessible to robust diagnosis in the infrared portion of the spectrum. Modern computing equipment offers orders-of-magnitude improvements in both the quantity and quality of measurement interpretation. Finally, recent advances in computer simulations of compressible convection now permit us to address these observations from a quantitative point-of-view. These advances in theory, coupled with the advances in observations, will allow a major improvement in our understanding of phenomena such as the turbulent diffusion of magnetic fields by confronting theory – such as the results of simulations – directly with high spatial resolution observations.

In addition to excellent angular resolution, it is necessary to be able to make accurate polarimetric measurements of the Zeeman effect across profiles of spectral lines formed over a range of heights in the solar atmosphere. In the past, progress in this area has been frustrated by the large amount of polarization produced within the existing solar telescopes at Kitt Peak and Sacramento Peak and by the technical demands of precision polarimetry through the Earth's atmosphere. Compensation techniques have recently been developed to allow measurements to be made at a level of about 0.1% using existing groundbased telescopes, and parallel advances in polarization analysis techniques and data acquisition will soon allow quantitative measures of the vector magnetic field with angular resolution of one arcsecond, or better. Substantial efforts are now underway at a number of US institutions to advance high-resolution solar polarimetry. Such work needs continued support at high priority. It will form an essential part of the magnetohydrodynamics initiative.

As for facilities, this ambitious initiative cannot be fully addressed with a single ground-based approach. First, we give highest priority to a new moderate to large aperture adaptive-optics telescope in the visible region and near infrared. However, this initiative must not preclude continued progress in the far infrared, where rapidly advancing technology, combined with intrinsic advantages of the far infrared (5 to 20 μ), may make a large-aperture infrared telescope a high priority. Second, this magnetohydrodynamics initiative includes moderate projects that are already started, as well as new ones. Third, the initiative will be greatly strengthened by, and will greatly strengthen, the Orbiting Solar Laboratory (OSL), presently NASA's top priority new start mission, whose UV telescope-spectrograph and X-ray imaging instruments provide powerful observational tools for studies that cannot be accomplished from the ground, and whose optical imaging capability will provide "space truth" for the much longer-term ground-based observations from LEST, and will help define evolving instrumentation for the LEST focal plane.

2.3.3.1 The Large Earthbased Solar Telescope (LEST)

Existing telescopes cannot provide the 0.1" resolution needed to measure directly such basic quantities as the strength of the highly concentrated and fragmented photospheric magnetic field. Both sufficient aperture and adaptive optics, in combination, are required to reach this goal from even the best ground-based sites. The United States, through a partnership between the National Solar Observatory, industry, and the Defense Department, has developed a world leadership position in the field of solar adaptive optics. Recently we have seen a significant advance in our ability to image the solar surface at close to the diffraction limit of moderate-aperture telescopes using this technique. This work, currently underway at a low level at the National Solar Observatory and Lockheed, should be vigorously pressed to an operational system at existing telescopes. Funding at a level of about \$1M per annum for a few years should allow the speedy completion of an adaptive optics system on an existing telescope which is demonstrably adequate for a large-aperture solar telescope.

Following the successful completion of these developments, the United States should develop a moderate to large-aperture high-resolution telescope, jointly with other countries. The United States is a participant in the *Large Earthbased Solar Telescope (LEST)* consortium, which plans to build such a telescope starting in 1992, and pending the results of the adaptive optics program and of the *LEST* final design study, the United States should plan to contribute up to 1/3 of the cost of that telescope (expected cost for 1/3 participation: \$1M design, \$15M construction, \$1M annual operation).

The *LEST* will be an ideal complement and long-lived extension to the *Orbiting Solar Laboratory*, a space mission for high-resolution solar studies in the optical, ultraviolet, and X-ray regions. (*OSL* is discussed in Section 3.3.1 below.) Whereas the hallmarks of *OSL* are uniquely high and uniform angular resolution, and unique access to the ultraviolet and X-ray regions, the hallmarks of *LEST* are large aperture, precision polarimetric capability, longevity, access to the near infrared (routinely out to 2.2 microns), and flexibility of instrumentation. The *OSL* will obtain visible light images and spectra in selected spectral lines, and continua with angular resolution and stability that could not be matched by any conceivable ground-based telescope. Because *OSL* is a free-flying telescope in a polar orbit, however, it will have no flexibility for changing its observing capabilities as new scientific and instrumental opportunities arise, and its lifetime (nominally three years, possibly longer) will of course not approach the 25-or-more year useful life of *LEST*. *OSL*'s design precludes the aperture and extremely low polarization required for the most sensitive measurements of three-dimensional magnetic field structures: although *OSL* will obtain uniquely highly resolved data on relatively strong magnetic fields, a telescope like *LEST*, with its large aperture (2.4 times the aperture of *OSL*) and extremely low polarization, is necessary to measure the full vector magnetic field of weak features. The *LEST* will build upon results from *OSL* characterizing the fine-scaled magnetic flux distribution and evolution at the solar surface, to investigate the full (non-potential) vector magnetic fields and their specific implications for energy transport and heating of the outer atmosphere. With the capability to probe deep in the photosphere at the 1.6 micron opacity minimum, *LEST* will also provide complementary data to *OSL* about the nature of convection and its overshoot, and the magnetic fields entrained therein. It may be able to provide important helioseismology information as a follow-on to the *GONG* (and in space, *SoHO* experiments), using adaptive optics to provide high-resolution over small fields of view for tomography of subsurface structure. Other key research areas abound, and will evolve over the long lifetime of *LEST*.

LEST will be the only new large solar telescope built with US participation since the mid-70's. It will complement and extend the aging US national facilities (McMath telescope complex on Kitt Peak, built in 1960, vacuum telescope feed added in 1973, and the Sac Peak facilities, the most modern of which dates to the mid '60's). Aside from these national facilities, there are few large university solar telescopes, so that the *LEST* will be of great importance across the community. In particular, *LEST* is expected to play a significant role in the training of advanced students in solar research, with great benefits to the vitality of the U.S. solar research community.

The *LEST* telescope will be the premier solar telescope on the face of the Earth. As befits such an endeavor, it is receiving scientific and financial support from around the world. The *LEST* foundation contains nine member countries: Australia, Germany, Israel, Italy, Norway, Spain, Sweden, Switzerland, and the United States. The international community of scientists represented by these nations provides a critical number of capable solar researchers able to utilize fully the capabilities of *LEST*. At the same time, the capital and operating costs will be jointly borne by the member nations. Thus, the United States will gain access to this unique instrument by providing no more than one-third of the total costs. As already

mentioned, the US costs will be less than \$20M, so that the *LEST* telescope will be an extremely cost-effective investment for the United States.

The *LEST* telescope is in a very mature state of design: It has been under study for nearly a decade, and more than 40 technical reports have been written on its design, scientific rationale, instrumentation, and site selection. A superb, proven, and developed site in the Canary Islands has now been selected.

The Solar Panel recommends in the strongest terms the rapid completion of the Adaptive Optics program, key to the success of *LEST*, followed by the funding of the US share of the *LEST* construction and annual operating costs.

2.3.3.2 Infrared Facility Development

The infrared solar spectrum offers several unique ways to study solar magnetohydrodynamics. The opacity minimum at 1.6 microns gives us the deepest look into the solar photosphere. At 12 microns, the emission lines arising from highly-excited states of magnesium, aluminum and other elements allow an unambiguous measurement of the strength of magnetic fields for most known features of the lower solar atmosphere. A powerful advantage for magnetic field research in the infrared is the quadratic wavelength variation of Zeeman splitting. This means that Zeeman components are cleanly separated at moderate field strengths and uncertain modeling of blended line profiles can be avoided. This advantage applies even with only moderate angular resolution. The McMath telescope of the National Solar Observatory is well suited to infrared solar research and, accordingly, several institutions are developing focal-plane instruments with modest resources to measure magnetic fields in the infrared. These efforts should be accelerated by increased funding to a level of about \$150K per annum.

The promise of the solar infrared for magnetic and other investigations is so great that a larger telescope than the 1.5m McMath is urgently needed. The need follows from the improvement of seeing that occurs in the infrared, combined with the decreasing resolution of a fixed aperture at increasing wavelength. Another reason for a larger aperture is the decreasing photon flux per spectrum line doppler width in the infrared. Three options are available, and all should be investigated: (a) join with our nighttime colleagues in construction of a 10m class telescope capable (with suitable protection) of doing solar infrared daytime work, (b) construct a new, large-aperture solar infrared telescope, and (c) upgrade the McMath telescope to a 4m aperture. It is well-worth aggressively pursuing all of these options. We do note however that the first option has the attraction that it is likely to be cost-effective for both the night-time and solar communities, and it would foster much-needed scientific interaction; similar cooperation would also obtain for the McMath upgrade, as this telescope could also be used to great advantage for stellar observations, in particular for asteroseismology. The singular attraction of the second option is that the telescope could be designed to do an optimum job from the start, and it could be placed in an excellent infrared site. The third option offers a rapid intermediate solution (in both cost and capability) to the need; the main experimental compromise is that it falls short of the desired angular resolution in the 12-micron region. The cost estimate for a 4m primary and 6m tracking mirror system (using cooled, actively-supported aluminum mirrors) is \$7M, including instrument upgrades and a 25% contingency. As already noted, this option also would provide an upgraded facility for solar-stellar research.

The Solar Panel recommends that detailed definition studies be carried out in the near future on the several approaches to development of infrared facilities, and that development of an appropriate facility be carried out later in the decade.

2.3.4 Moderate Initiatives

During this decade ground-based instrumentation offers the only practical approach to measurement of vector magnetic fields and electric fields in the photosphere and chromosphere and high-resolution imaging and spectroscopy of the corona, both during and outside of solar eclipses. These moderate initiatives are all of sufficiently small scale to allow them to be accomplished from a healthy grants program at NSF. Our goal here is simply to list examples without assigning priority order: The peer-review process, not this document, should determine when and how they are done.

In arbitrary order, the most important moderate initiatives include:

Global Solar Dynamics

The relationship between large-scale flow fields and long-term trends in solar activity is largely unexplored. The initial observations of "torsional oscillations" have been confirmed: The torsional oscillation represents a zone of enhanced latitudinal shear, and its migration from the poles to the equator is definitely

associated with the location of magnetic activity. Since the solar dynamo depends in part upon the existence of shear flows, these oscillations may play some role in the magnetic field generation process; whether or not this is the case, and if it is, exactly what this role might be, remains largely unresolved. The amplitude of the circulation associated with the activity is much smaller than that of various other solar velocity fields, and is therefore difficult to measure reliably. Observations from a single site do not allow us to remove the non-circulatory velocities by time-averaging. The most effective filter requires that we sample the non-circulatory velocity pattern uniformly in time over the lifetime of the process we wish to eliminate. A suitable network of sites will be necessary to address this objective from the ground, perhaps similar to the GONG network. A study is required to specify fully the individual telescopes and network necessary to carry out this project.

Gravity Modes in the Solar Interior

Oscillations of the solar interior for which buoyancy is the restoring force are expected to be excited within the solar radiative zone. These "g modes" are confined to cavities which extend roughly from the core to the bottom of the convection zone. They should thus be far better indicators than p modes of conditions deep within the energy-generating solar interior. Many attempts have been made to observe g modes, but to date there is no consensus on a positive detection. The information that the g modes promise on the solar interior is unique and valuable, so efforts to overcome the observational difficulties must be pursued. The observation of g modes is challenging because their periods are long, their amplitudes are expected to be weak, and the spectrum is expected to be very crowded. The main observational problem is to suppress the large background noise produced by supergranulation and active regions. A program to successfully detect and measure g modes will require several phases. First, funding must be provided to explore methods of detecting g modes. This will involve developing new observational techniques to suppress the high background noise produced by the Sun itself. Second, after a promising technique is developed, funding will be required to produce a demonstration instrument capable of producing convincing preliminary results. Finally, the long periods and crowded spectrum of g modes mean that helioseismic-quality measurements will not be possible from a single site, and either a ground-based network or a space mission will be required. The former would involve funding of the magnitude of the GONG project.

A Solar-Dedicated Frequency-Agile Radio Array

In solar flares, brightness temperature spectra (as distinct from flux spectra from a single telescope) can provide important diagnostics of the flare plasma, particularly the electron energy distribution/temperature and magnetic field strength. In active regions, spectra provide unique measurements of the coronal magnetic field. Three small dishes are presently being added to a solar dedicated, frequency-agile (1 - 18 GHz) array at Owens Valley, California, to expand the array to five dedicated telescopes. The power of the array lies in its ability to obtain detailed microwave spectra on time scales of seconds. It is highly desirable to increase the number of telescopes in the Owens Valley array to 8, giving 1260 u-v plane measurements. It would then rival the VLA in its solar imaging capability, surpass it in its spectral coverage, but would be dedicated to solar work.

A Large-Aperture Reflecting Coronagraph (LARC)

Heating of solar and stellar coronae, acceleration of solar and stellar winds, condensation of coronal plasma above active regions, and instabilities leading to coronal transients and mass ejections are among the fundamental astrophysical problems that would benefit greatly from the improved observations of the solar corona offered by a large aperture reflecting coronagraph (LARC). This concept overcomes most of the limitations of conventional refracting coronagraphs. Such a coronagraph has no fundamental restriction on aperture size. Because it is achromatic, the LARC can simultaneously observe multiple wavelengths, and can also remove the dust component that constitutes a major portion of the sky background through rapid image cadencing. It provides extended spectral coverage from the UV into the IR, and operation in the IR would further reduce the sky background. Indeed, a large aperture reflecting coronagraph would be superbly suited for solar IR observations. Such a coronagraph simplifies heat-flux rejection, and can be designed to offer extremely small net polarization. Internally-scattered light, the historic drawback of reflecting coronagraphs, can now be suppressed by superpolishing techniques. Prototype reflecting coronagraphs of 5cm and 15cm aperture operated at NSO/SP have demonstrated their ability to measure coronal structures that are much fainter than would be measurable with conventional refracting coronagraphs of comparable aperture.

A 1-2m aperture LARC could measure magnetic field structure at many heights in the corona, providing thereby the key to understanding coronal plasma processes. It could measure processes associated with electric current dissipation, MHD wave generation and damping, magnetic field strength and direction,

magnetic reconnection, flows and condensation in prominences, small spatial scale dynamical phenomena such as the events thought to be involved in high speed solar wind streams, and the mechanisms giving rise to coronal mass ejections. It could make excellent low-scattered-light photometric measurements of disk features, and could also make many nighttime observations requiring low levels of scattered light. The LARC, with its high spatial resolution, would neatly complement the high spectral resolution offered by the small reflecting coronagraph onboard SoHO.

Tomography of the Convection Zone

Early studies of the hydrodynamic structure of the solar interior through observations of pressure-driven (p) acoustic modes of oscillation provided a 1-dimensional description of the thermodynamic properties of the solar convection zone and interior. More recently the question of 2-dimensional structure has been opened, in the study of the solar rotation rate as a function of depth and latitude. The opportunity to study the 3-dimensional structure of subsurface layers – what has come to be called “tomography” – is now before us. Inhomogeneities produced by convection, large scale flows, and dynamo action all show promise of detection. There is reason to believe that tomography will provide the ability to probe the near-surface regions on the unseen hemisphere, leading to predictions of active centers that will rotate into the solar hemisphere that is visible from Earth.

Observational requirements include high spatial resolution (CCD formats ≈ 4096 -square), full-disk field of view (small-aperture active-optics telescopes), high signal-to-noise ratio (CCDs with large full well in combination with suitable narrow-band filters), and near-continuous observations over several days (a campaign mode is adequate, since the phenomena are not long-lived).

Macroscopic Electric Fields

Remote sensing of both quasi-static and wave-related macroscopic electric fields opens up a new diagnostic technique for particle acceleration and energy dissipation in the solar chromosphere and corona. Quasi-static transverse fields of order 10-100 Volts per cm are expected in reconnection models of flares. We would expect these fields to be canceled by polarization of the moving plasma. However, they would be detectable in a non-comoving population of neutral hydrogen. Whether a sufficient emission measure of non-comoving HI exists in the possibly highly filamented neutral sheets of a flare volume is a matter that can be settled only by electric field measurements. Current discharge flare models, on the other hand, predict large parallel E-fields, whose intensity may also reach 100 V/cm or more. Again only sensitive E-field measurements can determine the emission measure of HI that might exist in such double layers. In addition, wave- or turbulence-related E-fields of comparable 10-100 V/cm intensities have also been predicted in some flare models.

A technique using the transverse Stark effect in the high Paschen lines has been shown to yield sensitivities in the 10V/cm range, and observations with such a CCD “electrograph” are now underway at the NSO/SP Evans facility. Several directions appear to be promising in future application of this new technique. One is development of an imaging electrograph using a narrow-band filter instead of a spectrograph to study the two-dimensional distribution of the transverse electric field component. Such an instrument might use a liquid crystal birefringent filter as a monochromator to achieve ease of tunability over several spectral lines. Another direction is to build an electrograph optimized for the Brackett and Pfund series lines. The same wavelength-squared advantage used in infrared magnetic measurements at 1.6 and 12 microns could be realized by such an instrument.

Precision Solar Photometric Telescopes

Progress in measuring and understanding the Sun’s radiative outputs, stellar light variations, and the impact of solar variations on the Earth’s climate and atmospheric chemistry requires high precision and assured continuity in several kinds of photometric and radiometric observations of the Sun and Sun-like stars. These data, obtained from the ground and from space, are essential for improved physical understanding of the Sun’s present, past and future variations in the EUV, UV, and total radiative output.

The essential item of hardware for the solar component of these studies is a stable, well-characterized, low-scattering system for precision solar photometry. This system would include a small telescope, a monochromator, a large CCD detector and a modern data acquisition system. At least two of these instruments would be deployed at suitable sites, and manned by staff experienced in highly reproducible, carefully documented photometric observations.

2.3.5 Interdisciplinary Initiatives

In this section we describe several initiatives important for solar physics, but also important to other disciplines, and whose funding would come from outside the normal solar physics sources. It is thus not within the capability or purview of the traditional funding sources for solar physics to make any of the initiatives described in this section happen. Our intent here is simply to recognize that each and every one of these projects will allow us to learn something interesting and important about the Sun. On the basis of their interest to solar physics, they can be placed in rough priority as follows:

Neutrino Research

Neutrinos produced in the solar core, as a result of the nuclear reactions that give stars their long, stable lifetime, are predicted to have a mixture of line and continuum energy distributions. There are now two experiments which are sensitive only to the relatively rare, but high energy, ^8B neutrinos arising from a side-reaction of little energetic importance in the Sun; these experiments – the US Homestake mine experiment and the Japanese/US Kamiokande II collaboration – show consistent results, both at a level statistically significantly below that predicted by theory.

The next steps are to measure the energy spectrum of the electron-type ^8B neutrinos (as will be done by the Sudbury Solar Neutrino Observatory deuterium experiment, a Canadian/US/Great Britain collaboration, and by the liquid argon detector being developed by CERN and Italy), to measure the time-dependence of the neutrino flux (as a function of solar cycle as well as on the much shorter time scales associated with solar flares), and to determine the solar neutrino flux from the p-p reactions which play the central role in the energetics of the solar core. Unfortunately, the US participation in the two ^{71}Ga experiments now underway (the GALLEX experiment, principally funded by West Germany, Italy, France, and Israel, and the SAGE Soviet-American experiment) is relatively minor. Projects which are now under study will allow the energy spectrum of low-energy neutrinos to be mapped out (using, for example, low temperature detectors). Both the neutrino flux measurements and the neutrino spectroscopy are essential for progress in understanding the physics of the solar core (and hence the cores of other stars); indeed, it can be argued that such neutrino spectroscopy is as crucial to a thorough test and understanding of stellar structure and evolution as photon spectroscopy has been to fostering astrophysical developments over the last century. It is critical that these future developments be well supported.

NRAO Millimeter Array (MMA)

Exciting opportunities exist for high spatial resolution solar mm-wave studies using the array envisaged by the National Radio Astronomy Observatory. This wavelength domain is one of the last frontiers of radio astronomy. A key attribute of the *MMA* is that its spatial resolution is comparable to that now obtainable at other wavelengths, ranging from the optical to the X-ray domain – of order 1 second of arc; furthermore, at these short wavelengths, one can observe far deeper into the solar atmosphere than is possible at cm and longer wavelengths.

The science problems which can be attacked by the *MMA* are manifold. Consider, for example, mm-wave radiation from solar flares: At the lower chromospheric level, it likely to arise from thermal bremsstrahlung, allowing one to relate radio wave brightness to the density-temperature structure in the heated regions; relative timing of mm-wave vs. cm-wave bursts should then help distinguish among the possible causes of this heating. High time resolution studies of mm-wave flare continuum emission from 10-100 MeV electrons, and comparison with continuum and nuclear gamma-ray line observations, will constrain models for the as yet poorly understood near-simultaneous acceleration of electrons and protons to very high energies. Mapping of solar active regions, filaments and prominences which takes advantage of the partial polarization of mm-waves (resulting from the difference between x mode and o mode emissivities) will inform us about the magnetic field strength and topology at heights greater than the photosphere (where most magnetogram data apply). The arcsecond resolution of the *MMA* will help to understand why coronal holes are brighter than quiet regions in mm-waves, contrary to what is observed at almost all other wavelengths. Thus, there is wide recognition of the *MMA*'s outstanding potential for solar research, but it is important that adequate time be devoted to solar studies, and that the technical challenge of providing the desired data be met, for significant progress will surely result from applications of this array to solar studies.

An Antarctic Observatory for Long-Duration Observations

South Pole observations avoid two significant disadvantages of low-latitude networks, i.e., the need to merge observations from different instruments and effects of diurnal fluctuations in observing conditions at each site. Additionally, the South Pole offers better than arc second seeing and extraordinary infrared

observing conditions. The scientific benefit of a South Pole facility, which could be used for a number of different investigations by different groups, is significant for the study of solar activity variations over time scales of hours to weeks. Such a benefit has been realized for helioseismology and could be used to advance our understanding of solar activity in the same way.

The Canadian Compact Cm/dm Array

A study of a compact synthesis array for decimeter/centimeter waves is presently underway by Canadian radio astronomers; an international collaboration may be sought. The present concept has about 100 antennas, each about 12 m in diameter, occupying an area about 2 km in extent. This array would have a spatial resolution in arcseconds approximately equal to the wavelength in centimeters, and operate between about 0.4 and 5 GHz (possibly to 15 GHz). It would have a time resolution of 1 s or less. Its most important property for solar studies is the excellent u-v plane coverage in the snapshot mode (approximately 5,000 samples) that is needed to make high quality images (dynamic range > 100) in circumstances where the brightness distribution is changing. With such an array it would be possible to make definitive studies of the quiet Sun, active regions, and flares. It is particularly important to have flexibility in choosing observing frequency, as lower frequencies arise preferentially from greater heights, allowing changes of atmospheric structure with height to be measured.

Stellar Oscillations

The measurement of the stellar analogues of solar global p-mode oscillations will provide unique constraints on the physical structure of stellar convective zones and thereby test interior models. In addition, observations of the rotational splitting of such modes will yield the depth-averaged internal rotation rate. Comparison of the internal rotation rate with the surface rate, obtained from either line broadening measurements or modulation of the stellar flux by asymmetrically distributed surface active regions, will provide the first direct information on a fundamental parameter in dynamo theory, namely, differential rotation. The scaling of oscillation amplitudes with stellar parameters will elucidate the physics of the excitation process (e.g., stochastic excitation should scale in a different manner than other instability mechanisms). Finally, the observed mode frequencies can provide important new constraints on evolutionary processes. All of this information is central to understanding the structure, evolution, and internal dynamics of our own star, the Sun. The detection of stellar oscillations is the classic "photon-starved" problem where every increase in aperture yields gains. However, long uninterrupted blocks of time are required for success in asteroseismology. Hence, a facility that can be dedicated to programs of this kind is essential to progress further in the direct study of the interior structure of solar-type stars. A modest first step would be to construct several sets of identical focal plane instruments, each fed by an optical fiber. These could then be deployed at existing moderate-aperture telescopes (2-m or larger) at different longitudes in a campaign mode, to provide early measurements of key stellar seismic parameters on the brighter Sun-like stars.

Stellar Magnetic Activity

Stellar activity on both rotational and cyclic time scales is being investigated for a sample of solar-type stars and a sample of stars that spans a broad range of physical parameter space. Of particular interest are the various activity cycles and large luminosity variations that have appeared after only a couple of decades, foreshadowing occasional variations in the Sun at widely spaced and unpredictable intervals. Thus far, this fundamental and extremely important study has received but little attention and support from the federal funding agencies. The relevant stellar properties include mass, effective temperature and gravity, rotation rate, age, metallicity and fractional convection zone depth. An especially critical boundary condition for dynamo theory occurs in the region of the Hertzsprung-Russell diagram where stars become fully convective, i.e., for spectral types later than about dM5. It is in this region where the nature of the operative dynamo is expected to undergo a fundamental change. We have no information on the nature of activity cycles, if they exist at all, in stars with wholly convective interiors.

At the very least, funding is required to maintain the important, if long-term, synoptic studies underway with existing facilities. However, because of the intrinsic faintness of many stars of interest, a large aperture facility is required to obtain synoptic observations of key activity diagnostics such as the Ca II K line. A 4 m-class telescope with modern instrumentation will permit observations of stars 2 magnitudes fainter than is possible with existing smaller and older facilities, thus expanding the sample size by more than a factor of 10. In this way, meaningful statistics on the properties of the activity in the fully convective, intrinsically faint M dwarf stars can be obtained.

2.4 Conclusions and Summary

During the next decade, ground-based solar physics will enter a new observational frontier enabled by advances in adaptive optics, high precision polarimetry, and infrared imaging: direct observations of interactions between solar surface motions and solar magnetic fields on the sub-arcsecond spatial scales which theory predicts are relevant to the evolution of solar surface magnetic fields and energy input into the solar outer atmosphere. These new capabilities complement the new view of the solar interior which helioseismology has revealed over the past decade. As a starting point, we therefore strongly encourage the continued vigorous support of the *GONG* project (which will push the frontiers of exploring the solar interior from the ground); and we strongly recommend, first, the immediate development of adaptive optics necessary for high and uniform angular resolution optical observations, with the specific aim of building, together with international partners, the *LEST* facility to attack the frontier of high angular resolution solar surface observations; second, the vigorous development of infrared imaging and spectroscopy instrumentation, together with development of a detailed plan for a large-aperture infrared facility; third, a concerted effort to implement the moderate-scale initiatives listed in Section 2.3.4, and fourth, support for the interdisciplinary initiative listed in Section 2.3.5.

3. SPACE OBSERVATIONS FOR SOLAR PHYSICS

3.1 Introduction and Summary

Beginning with the early V-2 rocket flights, the observing capabilities opened up by access to space have led to a continual flow of discovery and understanding in many branches of solar physics. The new techniques made possible by space — new wavelengths, unparalleled “seeing”, and photometric stability — have formed a large part of the modern renaissance of solar physics. The solar observational domain has at the same time broadened tremendously, now ranging from neutrinos from the solar core to resonance-scattered interstellar gas at the heliopause.

Much interest in solar physics is associated with magnetic activity: the dynamo, the surface magnetism in sunspots and faculae, solar flares and coronal mass ejections, and the solar wind itself. Observations during the last decade, with the *Solar Maximum Mission (SMM)* and other instruments, have provided new insights into the problems of explosive energy release and particle acceleration associated with solar activity. But in addition, surprisingly, the deep solar interior has stimulated flourishing new fields of investigation — led by the neutrino puzzle and the remarkable exploits of helioseismology. These new discoveries are just beginning to be reflected in the content of the U.S. space program in solar physics.

To meet the challenge of these new discoveries, we recommend the immediate development of approved missions such as the *Solar and Heliospheric Observatory (SoHO)* and the *Orbiting Solar Laboratory (OSL)*, together with the support and encouragement of small observational programs (sub-orbital, international missions, small Explorers, and individual experiments on various spacecraft). Among the proposed new missions beyond *OSL*, the solar community strongly endorses the *High Energy Solar Physics (HESP)* mission, a small-to-moderate mission capable of studying magnetic active regions and flares by emphasizing hard X-ray, gamma-ray, and neutron observations, through the maximum of the forthcoming solar cycle (ca. 2000 A.D.).

3.2 Ongoing Programs

3.2.1 U.S. Programs

There are no currently approved U.S. spacecraft dedicated to solar physics. The only NASA programs in observational solar physics approved at present consist of one instrument on the Japanese (ISAS) *Solar-A* (1991 launch), instrumentation on board the European (ESA) *Solar Heliospheric Observatory* (1995 launch), and the remainder of the small suborbital program (including two Max 91 balloon payloads, some other rockets, balloons, and one Spartan mission). In addition there are important interdisciplinary instruments with potential solar applications, e.g. the planned launches of the *Gamma-Ray Observatory*, *Ulysses*, and *WIND* in the early 90's.

One flight instrument (the *Ultra High Resolution XUV Spectroheliograph*) and one concept study for a major mission (the *Pinhole/Occulter Facility*) have been approved for Space Station *Freedom*. Depending upon the rapidity of deployment of the Space Station, and of its utility for attached payloads, it may become

a major factor in space observations for solar physics. The *Pinhole/Occulter Facility* is discussed further below.

The *Orbiting Solar Laboratory* is in a special category, in that its Shuttle-based predecessor was an approved mission in the past. It is very much an ongoing program and its approval to resume development for flight as a free-flyer in a polar orbit is anticipated in the very near future. We discuss it in detail in Section 3.3.1 below.

3.2.2 Non-U.S. Programs

At present there are a number of solar spacecraft already under development in all of the non-U.S. major space programs (Japan, Europe, U.S.S.R.). These consist of

- *Solar-A*. This Japanese spacecraft, to be launched in 1991, will observe high-energy phenomena in solar flares. It contains one major U.S.-supplied instrument, a soft X-ray telescope with a 1024×1024 -pixel CCD camera (pixel size 2.5 arc seconds). This will obtain the first soft X-ray images of the Sun from orbit since the *Skylab* Observatory of the early '70's, and the first not using a film readout. *Solar-A* also carries instrumentation for hard X-ray imaging and non-imaging X-ray spectroscopy.

- *SoHO*. This ESA mission contains three U.S. experiments: a solar oscillations imager for helioseismology, and white-light and UV coronagraphs for studying coronal mass ejections and the solar wind. The spacecraft will be placed at the L1 Lagrangian point of the Earth-Sun system, offering continuous sunlight. In addition to these experiments, the *SoHO* instrumentation will carry out detailed observations of the chromosphere, transition region, and corona with EUV and XUV instruments.

- *CORONAS*. This Soviet project consists of a series of spacecraft launches to study solar phenomena simultaneously with their influence on near-Earth space. The measurements will be made from the *Automatic Universal Orbital Station* with solar orientation, to be launched into a quasi-Sun-synchronous orbit between 72 - 82 degrees at an altitude of 500 km. Measurements of particular interest will be made with a soft X-ray telescope (*TEREK*) for location of solar outbursts. Other instruments (*IRIS*, *SONG*) will determine the spectra of gamma-rays and neutrons. The spectra and composition of solar cosmic rays near the Earth will also be measured. Additional instrumentation includes a radiospectrometer for the frequency range 0.1-30 MHz, and photometers to study solar oscillations. There are no U.S. experiments aboard the *CORONAS* spacecraft. Currently two *CORONAS* launches (I and F) are planned between late 1990 and 1992.

3.3 New Missions

3.3.1 The *Orbiting Solar Laboratory*

The *Orbiting Solar Laboratory* (*OSL*) is the prerequisite space mission for solar physics in the 1990s. It will break through the barrier of poor spatial resolution which has severely retarded studies of magnetic activity on the Sun. Earlier solar space observations have primarily emphasized wavelength regimes not accessible from the ground. The *OSL* combines UV and soft X-ray observations of the chromosphere and corona, with photospheric measurements from a diffraction-limited 1-m telescope totally free from atmospheric blurring. This will permit observations of basic phenomena on spatial scales comparable to the density scale height of the solar photosphere. Accurate measurements of physical properties free from non-linear spatial averaging over a wide range of varying conditions will be possible for the first time.

As a well-instrumented, long-lived and readily available facility, the *OSL* will be capable of conducting a wide and varying range of solar research. A primary goal for *OSL* research is the nature of solar magnetic fields from the deepest observable layers of the photosphere upward to high temperature regions of the solar corona. A particularly important location is where the solar plasma changes from domination by radiative and convective processes to magnetic control; processes in this region are fundamental in creating solar activity. Thus the dynamic interaction of magnetic fields with mass motions is another key goal of *OSL* research. A third major goal is to study magnetic energy storage in the atmosphere, and the conversion of violently released energy to high temperature plasma in phenomena such as flares. Many of these processes are currently mysterious even for as well-observed a star as the Sun. Solving these problems will give us more confidence that our understanding of processes elsewhere in the Universe is well founded.

The *Orbiting Solar Laboratory* will resolve the individual flux tubes that have widths comparable to the intergranular lanes of the photospheric convection (about 200 km or less) and will track their migration, intermingling, and interaction. At the same time, it will measure the response in the overlying chromosphere

and corona to these MHD interactions in the photosphere. This cause-and-effect observing capability is the core rationale for *OSL*, leading to knowledge of:

- How the interaction between the convection and the magnetic field drives the heating that sustains the chromosphere, corona, and solar wind.
- How nonpotential energy is built up in large-scale metastable configurations, how these configurations evolve (and possibly become unstable), and how the stored energy is released (including possibly in flares and coronal mass ejections).
- How magnetic flux in the photosphere is "processed" by turbulent convection, and caused to diffuse away from active regions. This apparently sows the seeds for a new magnetic cycle in the dynamo process that sustains the Sun's magnetic field.

OSL is an extremely well-defined and thoroughly-studied mission. Planning for the critical component, a large-aperture diffraction-limited visible-light telescope (the *Solar Optical Telescope*, or *SOT*), began 17 years ago. Indeed the *SOT* was approved for development as a *Spacelab* mission more than a decade ago, but the development was then postponed for programmatic reasons unrelated to the scientific merits of the mission. Since then, technical capabilities have increased greatly, so that today the *OSL* has scientific potential *far* transcending the original mission. *OSL* is the key mission for solar physics, and enjoys the highest possible endorsement of the community. The Solar Panel notes with satisfaction that the *OSL* is now at the top of NASA's Strategic Plan for Space Science, and urges in the strongest possible terms that its development be resumed as soon as possible.

3.3.2 The *High Energy Solar Physics (HESP)* Mission

The scientific goals of *HESP* – a new mission to study the active Sun and flares during the activity maximum toward the end of the decade – center on the mechanisms and processes of explosive energy release and particle acceleration associated with solar activity. These processes are at the core of the solar flare problem, and they play a major role in all of astrophysics, particularly in objects dominated by high energy processes. *HESP* will observe the high-energy radiations (hard X-rays, gamma-rays, and neutrons) which are the most unambiguous signatures of accelerated particle interactions. Observations of these emissions with high spatial resolution will allow the localization of the sources of the particles and the tracing of their transport paths. Observations with high spectral resolution will allow the deciphering of the rich information encoded in gamma-ray lines, such as abundances in both the ambient gas and the accelerated particles, beaming of the accelerated particles, temperatures and states of ionization of the ambient gas, and the structure of the magnetic fields. The combination of high spatial and energy resolution, by providing diagnostics which are qualitatively different from anything available so far, offers unique opportunities for resolving some of the most complex issues in solar physics (flare mechanisms, particle acceleration, coronal heating). Understanding of these issues will also be of great benefit to high energy astrophysics. In particular, *HESP* will provide information on:

- The nature of acceleration mechanisms, by determining the ratio of accelerated protons to electrons from observations of gamma-ray lines and continuum. An overabundance of protons would favor shock and stochastic mechanisms, while the overabundance of electrons would favor electric fields. The combination of high spatial resolution and energy resolution could distinguish sites where electron acceleration dominates from sites where ion acceleration is dominant.
- Angular distributions and magnetic field structures, from direct imaging of hard X-ray bremsstrahlung in the active flux tubes. The shapes of the nuclear deexcitation gamma-ray lines also reveal the angular distribution of the interacting ions, which in turn depend on the nature of the acceleration and transport of the fast particles and on the structure of the magnetic fields. With the combined angular and spectral resolving power of *HESP* it will be possible to determine angular distributions accurately as a function of position in the atmosphere.
- Abundances in both the ambient gas and in the accelerated particles, from the relative intensities of gamma-ray lines. These abundances include that of ^3He in the photosphere. The high energy resolution capability of *HESP* will allow the separation of many more lines than was possible with *SMM*, thereby qualitatively enhancing the power of the technique. Abundance variations shed light on mechanisms of mass motion in the atmosphere and turbulent mixing in the interior.
- Temperatures, densities and states of ionization of the ambient gas, from the shape of the 511 keV positron annihilation line. Recent galactic observations of this line with high energy resolution have yielded

information on the interstellar medium. No comparable solar observations of the 511 keV line have yet been carried out. Based on the analogy with the galactic case, we are confident that much new qualitative information will be forthcoming from high resolution observations of annihilation radiation from solar flares.

- Heating of the corona, by observing bremsstrahlung from electron acceleration in microflares and other non-thermal processes. If even minimal efficiency for 10 MeV proton acceleration accompanies the energy deposition in the solar corona, then the corona can also be observed as a steady source of 2.223 MeV line emission; that is, it has been shown that even if one part in several thousand of the energy needed to accelerate the solar wind is deposited in the corona by protons of energies greater than 10 MeV, the Sun would be a steady source of gamma-ray line emission. Because of its great sensitivity to the very narrow 2.223 MeV neutron capture line, *HESP* could detect the presence of ion interactions which heat the nonflaring solar atmosphere. The question of the heating of the solar corona could therefore be investigated with *HESP* in a novel way.

The *HESP* payload will consist of a single instrument, a Ge spectrometer that combines high spectral resolution for hard X-rays and gamma-rays with high-resolution imaging from modulation-collimator optics. It will also have the capability for observing meson-decay gamma-rays and neutrons using its anticoincidence shield elements. The instrument will have angular resolution below one arc sec, energy resolution on the order of 1 keV (over an energy range up to 10 MeV), and time resolution of < 1 s. Observations with *HESP* will characterize the evolution of solar activity from the beginning and through the maximum of Cycle 23. To carry out its mission properly, *HESP* should be accompanied with diagnostic observations of parameters of solar plasma in the $10^4 - 10^7$ K temperature range, and with vector magnetic field measurements in the photosphere. Such observations could be provided by the instruments on *OSL* if *OSL* is operating during the next peak of solar activity. (If not, *HESP* should carry XUV, EUV, and enhanced visible instrumentation capable of imaging and spectroscopy of the solar atmosphere.) *HESP*, as defined here, lies in the small-to-moderate mission category, and is consistent with the scope of the Explorer program. The Solar Panel regards *HESP* as the highest priority *new* mission for solar physics in the 90's, and strongly recommends its rapid development, so that it is in orbit by the next rise to maximum solar activity around 1999.

3.3.3 "Quick" Opportunities in Space

In addition to *HESP* and the on-going missions, we feel strongly that a full spectrum of space flight opportunity should exist and be exploited properly for solar physics. The small end of the spectrum — to which Freeman Dyson's comment that "Quick is Beautiful" applies perfectly — includes Small Explorers, Shuttle-based experiments (including GAS payloads), the suborbital program (balloons and rockets), partial payloads on various U.S. and international spacecraft, and small attached payloads on the Space Station. Many of these smaller, short time-scale opportunities have a major positive effect on the nature of the solar physics program because of the involvement of students and the impetus towards innovation in instrumentation.

Balloons and rockets will continue to be at the forefront of instrument development activities for future space missions. These vehicles can also produce highly valuable data. Long-duration balloon flights, for example, can offer 7-20 days of data, thus providing essentially mini-spacecraft missions at low cost for certain wavelength ranges (gamma-rays, hard X-rays, optical). The current Max '91 Solar Balloon Program is a good example of an initiative exploiting this capability, but has been the subject of major cutbacks. The *SPARTAN* program and other limited-duration experiments on board the Space Shuttles also deserve notice, and indeed have already produced important data in several branches of solar physics. Suborbital and other "quick" opportunities are the ideal vehicles for student training in experimental work, essential for the future growth of the discipline.

The Space Station *Freedom*, with proper planning and adequate transportation back and forth to orbit, could meet many of the requirements for small solar space instrumentation (as has the *Spacelab* program, in fact). For example, precise radiometric instruments could be deployed, intercalibrated, exchanged with new versions, etc. Such measurements would benefit solar and stellar astronomy as well as radiometry in general. The *Ultra High Resolution XUV Spectroheliograph (UHRXS)*, recently selected for flight on *Freedom*, should achieve spectrally resolved images with angular resolution of ≈ 0.1 arc seconds over the wavelength interval $\approx 6\text{\AA} < \lambda < 1,550\text{\AA}$, which is indicative of the potential that *Freedom* represents for solar physics.

3.3.4 Other missions

Many other important space missions have been proposed, each with unique capabilities for solar and related sciences. We do not prioritize these here and recognize that some of them will have to wait for some time, but we do think that their scientific content strongly warrants their eventual development. Some require deep space, and these will have increased priority in the eventuality of human travel to the Moon and the planets. Some of these missions have been well-studied, and others are just ideas at present.

- *The Pinhole/Occulter Facility*: The *P/OF* scientific objective is to provide sensitive, high-resolution observation of the solar corona, incorporating large-aperture UV and visible imagers as well as the crucial high-energy observations (hard X-rays and gamma-rays) at 0.1 arc sec resolution. The *HESP* mission defined above serves as a predecessor of the full-fledged Pinhole/Occulter high-energy experiments. The *P/OF* coronal observations would provide an ideal Earth-orbital complement to the *Solar Probe*, for its observations would record the "context" of the *Probe's in situ* measurements. As mentioned, *P/OF* has been approved as a concept study for the Space Station *Freedom*, and its development schedule will depend upon that of the Station.

- *Solar Polar Orbiting Imager*: Solar observations from above the solar poles, including imaging and stereoscopy in conjunction with observations from near Earth. The polar regions of the Sun play a unique role in the evolution of solar activity, particularly on solar-cycle time scales. A solar polar orbit would let us look directly at these regions for the first time, without the major uncertainties caused by projection from ecliptic-plane observations. A polar orbiter will also give a global view of the mid-latitude regions of activity and permit us to follow their evolution on the crucial few-week time scales not accessible from a single perspective in the ecliptic.

- *Solar Probe/Context*: While not a solar remote-sensing mission in the classical sense of solar astronomy, *Solar Probe* can make *in situ* observations from its unique perspective, within a few solar radii of the solar surface. True scientific productivity from *Solar Probe* demands the existence of facilities for "context" observations of the corona from one A.U., with state-of-the-art coronal imaging and spectroscopy; the scientific return from *Solar Probe* can be amplified many times by conducting high-resolution coronal observations before, during, and after the perihelion passage – it may be possible to carry out true tomographic remote-sensing observations, capable of defining the three-dimensional structure through which *Solar Probe* would fly. This is the aim of the *High-resolution Coronal Imager (Context)*. The *Context* mission addresses a major problem in astrophysics: How are hot plasmas in stellar atmospheric structures created? Through high-resolution imaging and spectroscopy, *Context* can identify the structures through which *Probe* has flown, in order to understand the environment of *Probe's* particles-and-fields measurements. Such a combination of *in situ* and remote sensing will be unprecedented in astrophysics.

- *Advanced Solar Observatory (ASO)*: The deployment of advanced instrumentation in all areas of observation, into a comprehensive facility for space observation of the Sun, represents a natural goal of the solar space program. Concepts for an *ASO* have been studied for the Space Station. The *Pinhole/Occulter Facility* and the *Ultra High Resolution XUV Spectroheliograph* represent the initial steps toward a comprehensive *Advanced Solar Observatory*.

- *Mercury Orbiter*: Unique solar physics observations can be made from a spacecraft orbiting Mercury. High-energy neutral emissions, such as hard X-rays, gamma-rays, and neutrons, will be considerably more intense than at 1 A.U. (about 10x for photons, but more than 1000x for neutrons). Solar energetic particles, when observed at 0.3 A.U., are less affected by the intervening interplanetary medium, and hence will more directly reflect the propagation of the particles accelerated in the flare region than they do at 1 A.U. Long-term observations of these flare emissions from Mercury could be carried out for a large part of Cycle 23 after the year 2000. Additional observations at other solar aspect angles can give valuable stereoscopic information bearing on the directivity of solar emissions or their height of origin. These observations can be made with small instruments (<25 kg) with modest power and telemetry requirements.

- *Solar-Stellar Activity Mission*: The stars teach us about solar activity by allowing the study of analogs to the solar mechanisms; they also give us rich fields for new discovery. Stellar magnetic activity can be sensitively studied with wide-field (one degree), high-resolution (few arc sec) soft X-ray observations, preferably arranged with observing sequences that allow broad ranges of time scales. A dedicated solar-stellar activity mission might also carry EUV instrumentation for monitoring stellar chromospheric activity, and visible-light instrumentation for stellar seismology.

- *Solar Watch*: a network of deep-space solar observing nodes in deep space can provide unique views of the Sun from different perspectives. Such stereoscopic viewing is essential scientifically, because of the globally variable structure that solar activity presents to us and because of its inherently three-dimensional structure. A global view is also essential for characterization of solar activity – on relevant time scales – at a level capable of supporting accurate predictions. This prediction capability is a prerequisite for human space travel in the future, for example to the Moon or to Mars, because of the threat posed by high-energy radiations. We envision a “Solar Watch” program beginning with fairly simple operational measurements, and building up to sophisticated research-class instrumentation in the future.

- *Solar Synoptic Observatory*: a permanent space facility for basic solar observations ranging from total irradiance to H-alpha flare patrol. This type of work is currently done from the ground using antiquated technology, as a service function for various commercial and government users (e.g., power distribution networks interested in service disruptions due to magnetic storms). Such data are often used for scientific purposes, because they uniquely cover the longer time scales. Both functions would improve dramatically – much improvement in precision would be possible, for example in sunspot records – if a permanent facility could be established, perhaps at geosynchronous orbit as a part of the NOAA meteorological satellite system.

- *Janus*: a mission to characterize both the origins and the results of the Sun-Earth interactions, largely by simultaneous remote sensing. The name Janus comes from the Roman god of doorways, represented with two faces for bidirectional viewing. The Janus mission would require observation both from deep space (e.g., the L1 point) and from a polar 24-hour platform. Janus would simultaneously tackle (a) the precise characterization of Sun-Earth relationships of all kinds, essential for the understanding of anthropogenic changes in the environment; and (b) the accumulation of solar data essential for prediction of solar and heliospheric activity – the “solar weather.”

3.4 The Space Exploration Initiative

A Presidential initiative is now under consideration to return human beings to the Moon and eventually to send them to Mars as well. While the ultimate objectives of this endeavor are not primarily scientific, this enterprise will inevitably affect solar research in strong ways: “applied solar research” insofar as solar high-energy radiations pose a danger to astronauts’ health; and “pure solar research” that can take advantage of uniquely valuable research platforms enabled by the initiative. We discuss these briefly here.

The Initiative presents both challenges and opportunities to solar physics. The challenges relate to the prediction of solar activity, a practical subject whose success is closely linked to our theoretical understanding of the underlying physics. We have addressed this prerequisite with the “Solar Watch” program described above, which will provide qualitative and quantitative improvements in the data base for solar activity forecasting. Deep-space observations of the invisible hemisphere of the Sun alone will appreciably improve activity forecasting via the early warning capability of active-region growth. It should be noted that the present solar maximum is (at least) one of the two largest on record, and that the “millennium maximum” will also produce large particle fluences.

Forecasts of space environment conditions will be more important than ever before when man returns to the Moon and starts for Mars. NASA made a huge effort during the Apollo program to keep aware of and avoid potential dangers from space disturbances. The Space Exploration Initiative will call for an even better effort because of the longer periods of astronaut exposure involved. The needs of society and those of solar physics coincide in research that will lead to a deep enough physical understanding of the Sun to permit accurate predictions of its magnetic activity, or to at least specify the limits of its predictability.

Opportunities for solar research are provided by the unique platforms made available under the Initiative.

The surface of the Moon has some explicit advantages for solar observations. It can provide a stable platform for extremely long focal-length instruments or interferometers, for example. A future Lunar Solar Observatory could therefore give us extraordinary capabilities, perhaps beyond those conceivable in free space. A particularly attractive idea is to build (on the far side of the Moon) a low-frequency radio interferometer. Such an instrument – in a crater far drier than Clark Lake or the Plains of Saint Augustine – would be in an ideal site because of the suppression of terrestrial radiation by the body of the Moon. The instrument would be capable of non-solar observations during its local nighttime.

The deep-space explorations will give us platforms for stereoscopic solar observations. Such observations (of the photosphere, chromosphere, and corona) will allow us to make true three-dimensional images of solar phenomena, probably a key qualitative improvement in many areas of solar physics. Also, the hidden

hemisphere of the Sun carries unique information about global processes, especially on the time scales (crucial for active-region development) comparable to the rotation period. For these reasons, an interplanetary network of solar observing instruments would be an extremely desirable goal for solar physics in space.

Finally, there is a sociological point to be made: Permanent inhabitants of the Moon, at some future time, will rather naturally have a strong interest in the Sun and its activity because of its practical significance to their survival. Solar observing facilities should have priority, and this priority should include both the early and late phases of development of lunar habitation.

3.5 Solar-Terrestrial Physics

By the time of the next solar maximum, environmental issues will likely be much more the focus of the space program than they are today. Already, better understanding of our environment is the premier achievement and most challenging goal of the space program. The EOS mission is a recognition of this. EOS will include solar irradiance monitors, but solar physicists will need to complement EOS with a research satellite dedicated to the predictive foundations of solar magnetic activity and solar-forced geomagnetic activity. While we do not make extravagant promises, there is little question that a vector magnetograph, a full-disk-viewing X-ray telescope, a chromospheric filtergraph, a coronagraph and a complement of high-energy burst detectors in Sun-synchronous orbit or at L1 would make strong contributions to our understanding of disturbances of the near-Earth space environment.

3.6 Conclusions and Summary

To meet the challenge of the next decade in space, we recommend the continued development of *OSL* and the other approved missions. Beyond these, our top priority for a new space project is a small-to-moderate mission capable of studying solar activity through the maximum of the forthcoming solar cycle (ca. 2000 A.D.); this *High-Energy Solar Physics (HESP)* mission will emphasize high-energy observations with an instrument of unprecedented spectral and spatial resolution, and sensitivity. We also strongly recommend the support and encouragement of small observational programs (sub-orbital, international missions, small Explorers, and individual experiments on various spacecraft), as well as ongoing space programs such as *Solar-A* and *SoHO*. Finally, we recommend expeditious development of the remaining missions listed in Section 3.3.4, each of which represents unique, first-class science.

4. TECHNOLOGY FOR SOLAR PHYSICS IN THE 1990s

4.1 Introduction

This section contains brief descriptions of technology development efforts that must be conducted during this decade to enable advanced research projects during the decade following AD 2000. Several of these efforts are now underway and should be continued. Some of the technology developments are common with other fields of astrophysics but others are unique to solar research. For those efforts that are well defined and already initiated, the implementation strategy is simple: finish the efforts as soon as possible and promptly convert the results of successful efforts into useful research tools. For less well defined activities and ones that this panel cannot foresee, the strategy for implementation is to let the peer review process assign priorities in the normal way. We note that although both NASA and the NSF have a mechanism for funding advanced technology initiatives, the scale of these two efforts is substantially different. Partly because of this difference, we list the specific efforts directed toward space and ground-based research separately, but note that there is often much commonality.

4.2 Ground-based solar physics

An observational science such as solar physics depends on improvements in technical capabilities for acquiring and reducing observational data. Two vital initiatives are required to insure a strong ground-based program both for the decade of the 1990s and beyond. The highest priority is a continuation of development of adaptive optical systems to allow existing and future telescopes to achieve high spatial resolution. The second priority is development of advanced data processing for handling the large data sets typical of solar observations.

4.2.1 Adaptive Optics

High spatial resolution measurements are needed for extended time intervals to investigate the detailed structures and dynamics associated with energy transport and storage, heating, and activity in the solar atmosphere. Image blurring and distortion make it difficult to obtain the needed data. Post-facto image reconstruction techniques in principle can be made to work for solar filtergrams, but real-time correction of the seeing is necessary for spectroscopic studies. A prototype solar adaptive optics system built by Lockheed demonstrated that a segmented active mirror could be made to function on the Sun, using high contrast features such as sunspots as targets. Current efforts are toward: (a) development of a more robust system that is easy to keep phased and that can track any arbitrary region on the Sun, locking on the low contrast granulation; and (b) interfacing such a system to an existing solar telescope in a user-friendly manner. Development of and experience with an operating adaptive optics system on an existing solar telescope is critical for the success of the *Large Earth-based Solar Telescope (LEST)* project.

4.2.2 Analysis of Extremely Large Data Sets

Progress in observational solar physics depends increasingly on analysis of large datasets of high dimensionality. Examples include helioseismology image time series (3-D), high speed flare spectroscopic imaging time series (4-D), and Stokes polarimetric multiband imaging time series (5-D). Data volumes range from a few gigabytes to a few terabytes. Current capability is only marginally adequate for the near term, and will be a major constraint later in the decade if not improved. Several requirements appear in handling large datasets. A need to monitor instrument performance and verify data quality requires quick access to small samples of the data spread throughout the set. Interactive processing of a subset is required to identify the systematic errors and biases, and the nature of gross defects. Finally, the need to reduce whole datasets to scientifically meaningful results depends on a pipeline analysis keeping pace with the data collection.

Raw computing power coupled with high data flow is necessary to maintain this currency. The development of suitable hardware will be driven by commercial needs far more than astronomical needs. Exceptions may be massively parallel processors or single language processors, which are still most common in research environments. It is critical to exploit useful developments, and to make available the most modern hardware practical for the needs of solar research. Solar physics has software needs that are seldom met by software developed for nighttime astrophysics. There is a need to develop specific solar research software and make it available to the solar community.

4.2.3 Instrumentation

A number of technological developments are important for the highest-priority ground-based solar research. Improvements in infrared narrow-band filters, polarizers, and photodetector arrays will contribute to continuing progress in measurement of magnetic and electric fields in the solar photosphere and chromosphere, as well as improved thermodynamic diagnostic capability in those same parts of the solar atmosphere. Optical photodetector arrays with shorter readout times than are presently available will produce an immediate benefit in any measurements such as the above, including development of adaptive optics. In some polarimetric applications, kilohertz rates would be ideal for processing of detected images in order to eliminate the undesirable effects of seeing. This need could be met by detectors with several (8) storage areas on the chip itself, along with efficient and rapid avenues to transfer the charge among the storage areas and the light-sensitive portion of the chip. Such devices would have to be developed in collaboration with the semiconductor industry. Superpolished mirrors are the key to the extension of coronagraph capability to the UV and IR regions of the spectrum, as well as to improved sensitivity and spatial resolution. Improvements in tunable birefringent filters using liquid crystals as electro-optic elements will bring direct benefit to all polarimetric observations, which encompasses virtually all of the above. Ongoing development of Fabry-Perot filter devices for very narrow-band imaging of the Sun should also be encouraged. Finally, for many applications, a device is urgently needed which allows spectral coverage simultaneously with imaging. This need would be met by an imaging Fourier transform spectrometer operating within a restricted bandwidth of the spectrum. This development will require a large advance in the speed with which the information from area detectors can be stored and processed.

4.3 Space-based Solar Physics

4.3.1 New Technology

The development of new technology for space observations, traditionally the domain of small space programs, has dwindled alarmingly with the lack of emphasis given by NASA to the suborbital programs and university groups. The recent successes of normal-incidence X-ray optics are a classic example of the kind of rewards that can be reaped by small programs.

Urgently needed technology areas include advanced detectors for all spectral ranges, mirror technology, filters, lightweight large structures and data systems. Many of these developments benefit more than one field of research, and should be energetically pursued in NASA's Office of Applications and Space Technology, in conjunction with OSSA.

4.3.2 Large Structures in Space

Most disciplines of astrophysics, including solar physics, envision large future instruments in space. These include telescopes of large aperture and/or focal length, interferometers for a variety of wavelengths, and large-scale occulters such as the *Pinhole/Occulter Facility*. Such structures can be made extremely lightweight and robust by using active servo control of the structure itself. This technology exists where needed for structures on the Earth's surface, for example in active-optics telescopes, but has never been utilized in space. NASA may also need this technology for its large engineering structures (for example, Space Station *Freedom* itself). We therefore encourage the orderly development of "Controls-Structures Interactions" techniques.

4.3.3 High-energy Instrumentation

A variety of new high energy (> 10 keV) radiation detection techniques which offer the potential advantages such as high spatial resolution, low background, polarization measurements, large detection area, and high spectral resolution at room temperature should be developed. These may include high pressure gas scintillation detectors, wide band-gap semiconductors such as HgI₂ or CdTe, position-sensitive germanium detectors, and crystal diffraction and channeling techniques.

5. POLICY AND RELATED PROGRAMMATIC RECOMMENDATIONS

5.1. University Research and Education

The discipline of solar physics is currently poorly represented in universities, and is consequently hampered in the development of a strong theoretical and experimental personnel base for future research. There are several initiatives that would specifically address this problem. First, the NASA Graduate Student Research Fellowship (GSRA) program, which funds graduate students semi-independently of a primary advisor, should be greatly expanded. This very successful program has commendably increased its student enrollment beyond allocated levels by ad hoc additional funding supplied by various OSSA Divisions, but we urge that NASA instead consider simply increasing the scale of this program. Second, the NSF graduate fellowships should be awarded over a flexible time period that would allow support to be shifted into the latter part of a student's graduate education, when he or she is most likely to be doing research (NSF Fellowships are currently awarded for the first three years of study). Third, stronger connections between universities and national research centers should be encouraged. This could be done by establishing additional cooperative research programs, expanding visitor programs (at both the postdoctoral and faculty level), and increasing the size of student visitor programs. The latter could be done through the NASA GSRA program, which at present funds students only at universities or NASA centers.

5.2. Facilitating Solar Research

Two steps can be taken by NASA and NSF to facilitate solar research through minor restructuring of existing funding programs.

1. NASA and NSF contracts/grants should have flexible funding periods, ranging from one year to five years, with the length of the funding period being determined by the quality and the requirements of the proposal.

2. NSF grants should allow for release time for teaching faculty, which could, for example, provide one half year of salary every three and one half years to support dedicated research time either at the home university or at another institution.

5.3. *Integrated Support of Solar Research*

It is important that both NASA and NSF take an integrated approach to the support of solar physics, particularly with regard to theoretical and observational research and to solar and related astrophysical research.

1. Whenever possible, a balanced support of theoretical and observational research should be provided; in addition, it is wise to provide a balance between theorists and observers tied to large research groups and/or projects, and theorists and observers who operate independently of such research groups. At the same time, we strongly urge NASA to improve its past and present record of funding only minimal amounts of science in conjunction with instrument proposals; past funding practices have led to the unfortunate situation that theoreticians are recruited as co-investigators on instrument proposals, contributing to the credibility of the proposal during peer review, but then are not funded to provide substantive scientific input prior to launch.

2. NASA Space Physics and Astrophysics should develop a mechanism for supporting interdisciplinary solar/astrophysical research. Other agencies should consider establishing similar arrangements, as appropriate.

5.4. *Computing*

1. Supercomputers: Although we applaud the recent initiatives in supercomputing by the NSF and, more recently, by NASA, we have some concern that this new capability is not optimally used. In particular, supercomputers are a singular resource for very large simulations (viz., calculations which consume of the order of 200 or more Cray X/MP CPU hours), which cannot be replaced by machines of the minisupercomputer class. However, national resources devoted to supercomputing in fact generally do not allow realistic access to such use of supercomputers. We urge the NSF and NASA to encourage the provision of additional resources to such very large scale computing, as has in fact been done by the NASA Ames supercomputing facility and, in isolated instances, by some of the NSF Supercomputing Centers.

2. Workstations: Workstations are becoming essential tools for both experimentalists and theorists in the analysis of their "data". For this reason, we recommend that contracts and grants should continue to be able to provide for both the purchase and maintenance of such workstations as a matter of standard practice.

3. Networks: Efforts to provide high speed digital networking capability to large numbers of solar researchers should be enhanced. Frequently used data sets should be made readily available via these networks.

5.5. *Theory Initiatives*

The NASA Solar-Terrestrial Theory Program (STTP), and its successor, the Space Physics Theory Program (SPTP), have made a commendable start in the support of theoretical work which is not directly mission-oriented. As a number of previous National Academy reports have noted, provision of such support — in addition to more mission-related theoretical studies — is essential for the health of the space physics disciplines.

These reports also noted that theory needs to be supported on two distinct scales: first, at the individual investigator level; second, at the level of group efforts with significant "critical mass". The STTP program indeed was created initially with the specific intention of responding to this second need.

However:

1. The current typical grant size of the NASA SPTP is well below what is desirable for support of "critical mass" theory groups at universities; this desired mean support level has been discussed by NASA, and projected at the roughly \$300K level, but has never been implemented. We recommend augmentation of the current program in order to increase the mean grant size to the previously-discussed support levels.

2. Much of current NASA theory grants to individuals is funded through the SR&T budget, in which there is substantial pressure to focus funding on directly mission-related work. This means that theoretical studies in solar physics, which are carried out by individuals but are not directly mission-related, are strongly discouraged, contrary to the recommendations of previous National Academy studies. We recommend that NASA modify the "ground-rules" so that such grants can be funded, based on the quality of the peer reviews.

3. Maintaining an appropriate balance between experimental programs, data analysis, and theory is a major challenge for both the NSF and NASA. We recommend that both agencies establish rough guidelines for balancing these programs, based on input from the appropriate advisory panels.

5.6 Recommendations by the National Academy of Sciences Study on Solar Physics from the Ground

Finally, we note that the National Academy of Sciences has recently published the report entitled "The Field of Solar Physics: Review and Recommendations for Ground-Based Solar Research" (National Academy Press, 1989), which contains the following recommendations which we endorse and incorporate into this report:

"1. Develop a coherent, well-defined infrastructure for solar physics within NSF, with that agency properly assuming the lead role in support of basic research in ground-based solar physics. Thus the committee recommends that the internal structure for funding of solar research within NSF be changed so that support for both grants and centers is administered by a single entity within NSF whose primary responsibility is solar physics. Such a reorganization will permit the development of appropriate advocacy within NSF, the definition of an overall coherent approach to the subject, a unified vision of the field's national facilities and university grants program — its scope and its development — and the implementation of new efforts. The directorate in which to place the recommended section could be either the Geosciences Directorate (the residence of support for solar-terrestrial sciences and the High Altitude Observatory) or the Mathematical and Physical Sciences Directorate (the residence of support for astronomy and the National Solar Observatory). Placement of the recommended section is a matter for NSF decision. The committee believes that such a section will benefit the nation's solar physics efforts.

2. Support and encourage university programs in experimental and observational solar physics and take steps to strengthen the partnership between, on the one hand, federally supported research centers and, on the other hand, universities. In particular, the committee recommends that specific programs to enhance education and training of students in solar instrumentation and observational techniques be established in the university community and that those universities willing to commit themselves to such programs receive support for the extended periods required to carry out such efforts. In addition, the committee recommends that more effective partnerships be forged between federally funded centers and universities—partnerships involving the exchange of faculty and technical staff, hardware and software, and workshops and short courses.

3. Protect newly funded initiatives in solar physics by ensuring their continued support until they are completed. Unless funding for such initiatives can be assured within the limits imposed by general federal budget restrictions, avoid pursuing additional new initiatives. The committee further recommends that NSF refrain from commingling funds targeted for new initiatives with base-level support funds in response to budget-cutting pressures."

The second and third points apply equally well to the solar programs within NASA, and we hence also recommend them to NASA.

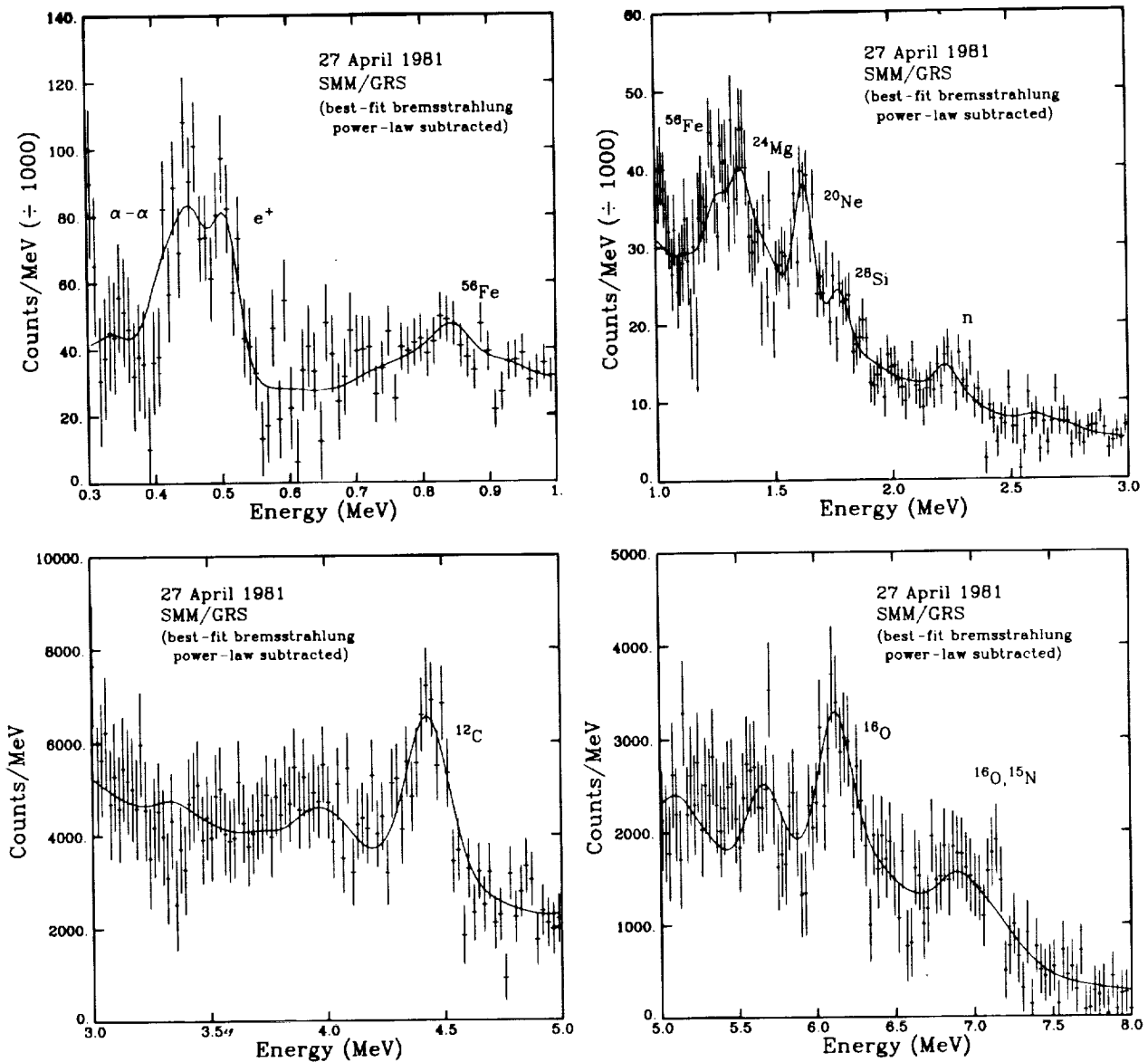


Figure 1. Observed gamma-ray spectrum of a solar flare. The comparison of the calculated spectrum (solid curve) with the data allows the determination of abundances of both the ambient gas in the gamma ray production region (thought to be the chromosphere) and the accelerated particles (thought to be accelerated in the corona). The aim of HESP is to improve our understanding of these gamma-ray spectra.



Figure 2. The solar X-ray corona photographed on September 11, 1989 from a rocket carrying a normal-incidence X-ray telescope. Normal-incidence optics represents a great advance over previous methods of solar X-ray imaging and will be the basis for high-resolution X-ray imaging on the Orbiting Solar Laboratory. Image courtesy of IBM Research and the Smithsonian Astrophysical Observatory.

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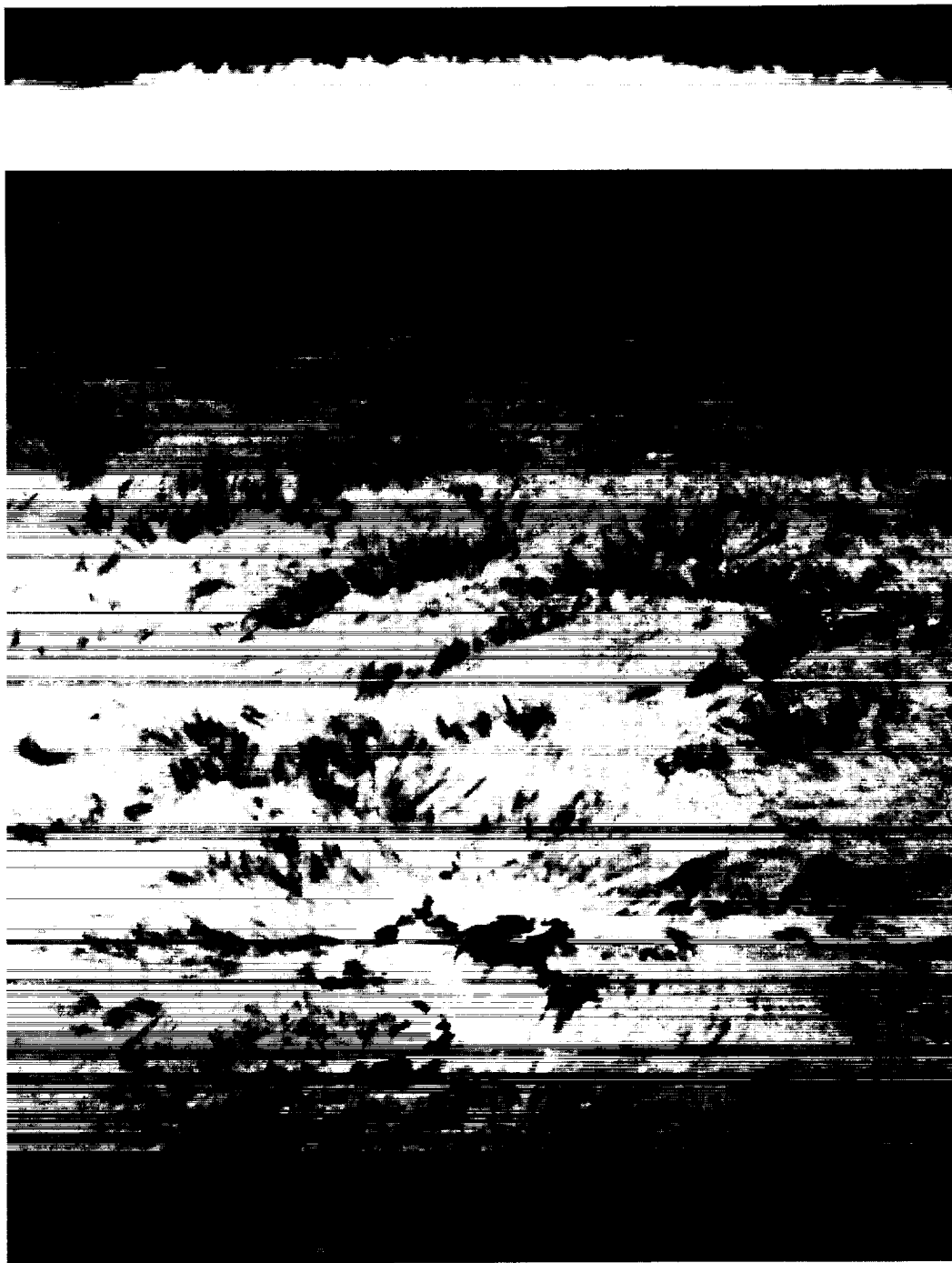


Figure 3. The solar chromosphere, imaged in H-alpha light at the Sacramento Peak Observatory. Spicules are seen near the limb as dark thread-like features (bottom), and are seen in emission above the limb (top). Spicules may be very important to our understanding of the energy balance of the solar atmosphere. Unfortunately, they are only poorly resolved in existing ground-based telescopes, but they could be thoroughly investigated using the high-resolution capabilities of LEST on the ground, or OSL in space.

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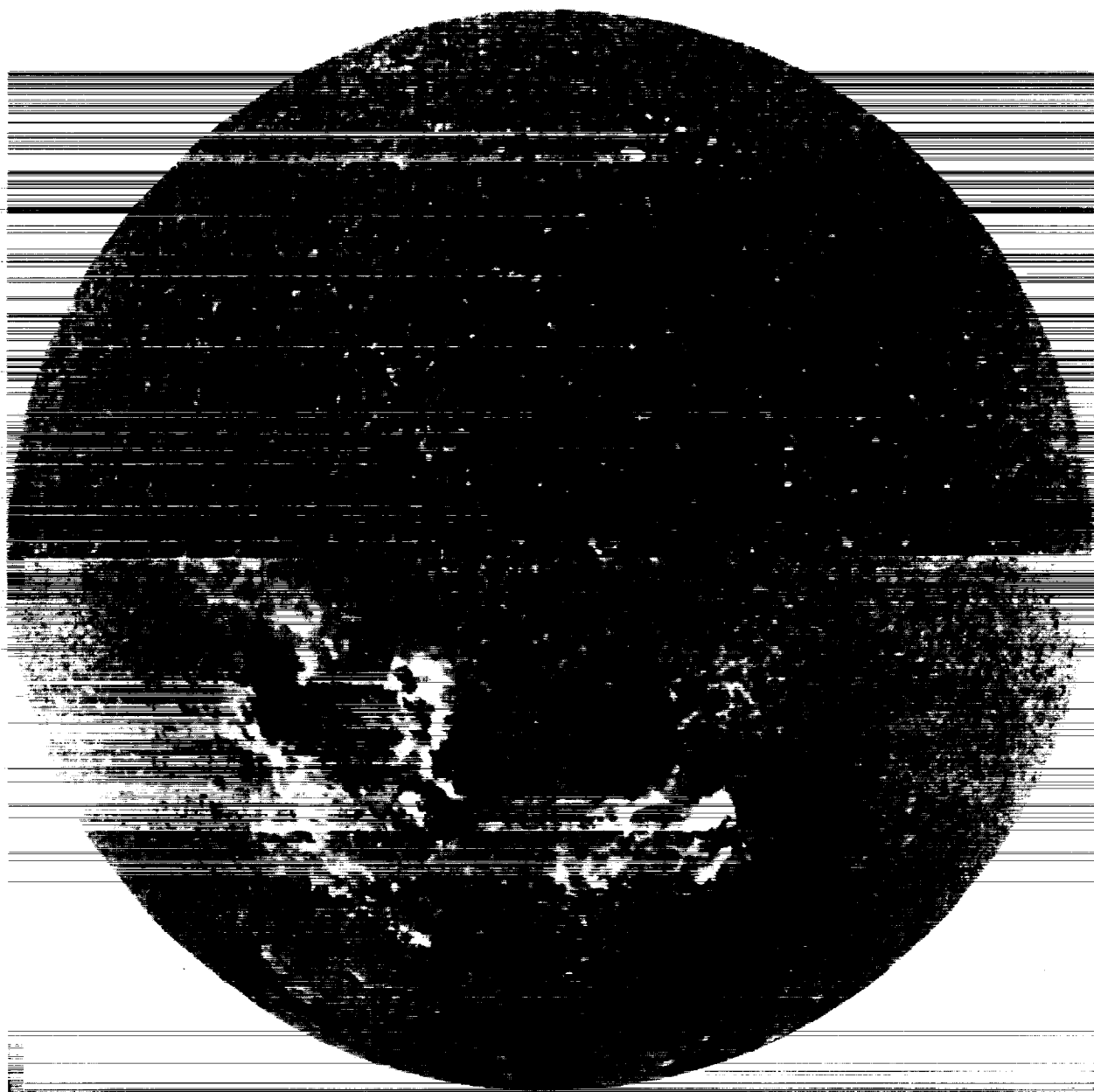


Figure 4. A composite magnetogram image, with the bottom half showing the magnetic pattern at maximum of the 11-year solar magnetic activity cycle and the top half the pattern at solar minimum. The dramatic change holds important clues to the nature of the magnetic cycle. It is important that new high-resolution observations, both from OSL and LEST, follow the changing magnetic patterns, and their consequences in the overlying atmosphere, throughout a large fraction of a solar cycle.

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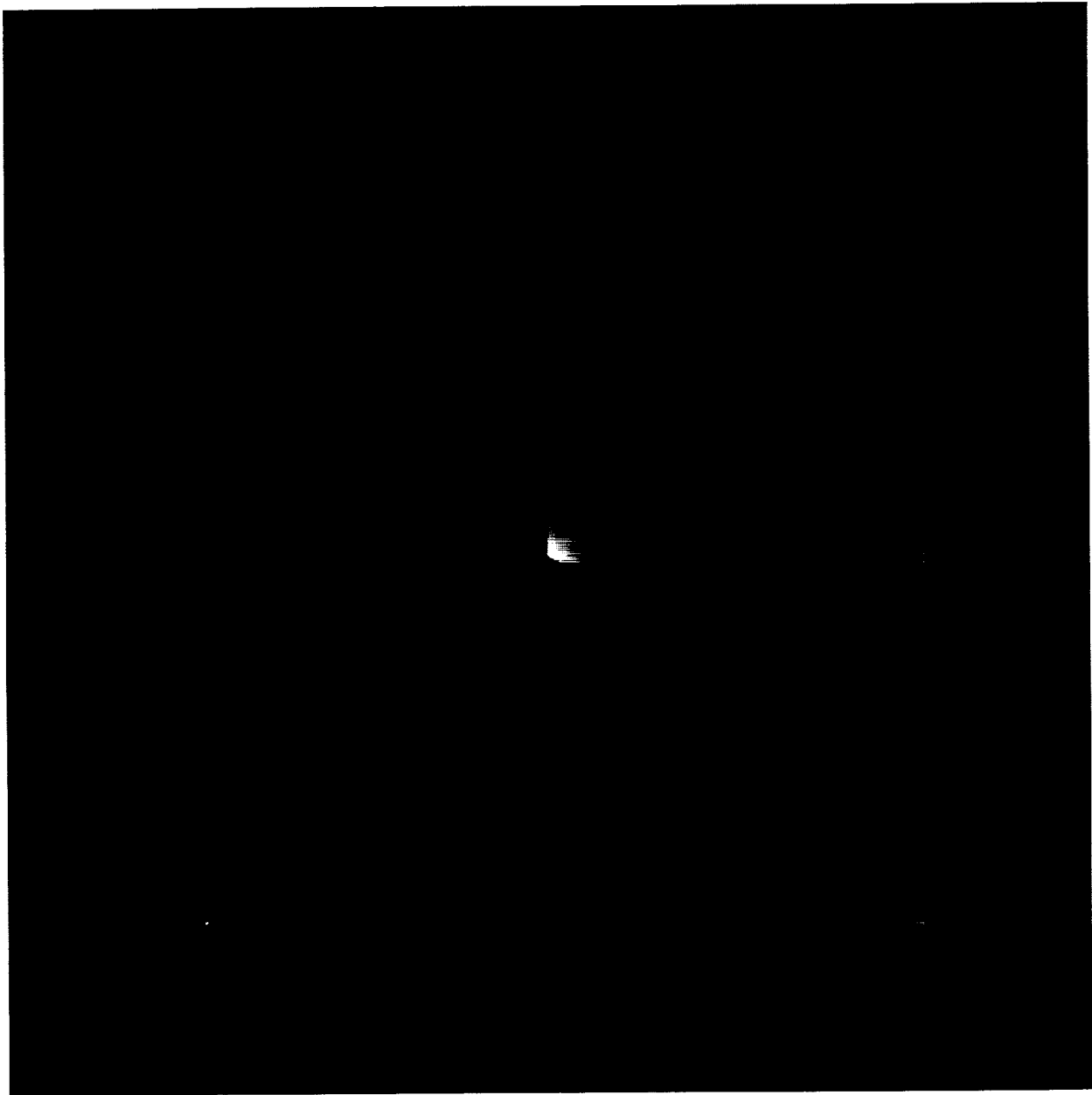


Figure 5. A computer representation of the two-dimensional spectrum of some of the 10 million solar oscillation modes. This covers the range of degrees from 0 to 150 (from left to right) and frequency from 2 to 5 mHz (bottom to top). These observations, made in a single day, do not have sufficient frequency resolution for accurate characterization of solar internal structure or rotation; needed are continuous observations for extended periods, such as are planned with the GONG experiment as well as helioseismology instruments on the SOHO mission.

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